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CLOUD SYSTEMS AND PRECIPITATION PROCESSES IN PACIFIC COAST STORMS

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ABSTRACT

From the records obtained during the Weather Bureau Artificial Cloud Nucleation Project carried out in western Washington State during the winters of 1952–53 and 1953–54, it is possible to study the nature of some of the precipitation processes evident in that locality, and to form a preliminary generalized picture of certain types of cloud systems involved. Evidence is presented of natural seeding mechanisms and of the growth of hydrometeors by diffusion, coalescence, aggregation, and accretion. Typical wintertime cloud systems, and the attendant precipitation processes are illustrated.

1. INTRODUCTION

The systematic investigation from aircraft of the physical processes involved in the production of precipitation is relatively rare. The many flights into winter storms in western Washington State by the cloud seeding aircraft of the Weather Bureau Artificial Cloud Nucleation (ACN) Project during the winters of 1952–53 and 1953–54 provided an excellent opportunity for the observation and study of precipitation processes and the cloud systems related to them. During a typical operation, one of the airplanes would orbit over a relatively small geographical area for several hours while the storm elements moved past it. During such periods, the flight meteorologist on board kept a detailed log of the cloud conditions and, when feasible, took photographs of the changing meteorological situation. In addition, cloud particle samples were taken, and air temperature, air speed, pressure altitude, and icing rate were automatically recorded.

From these records, it has been possible to derive evidence, either by direct observation or by inference, concerning the nature of some of the precipitation processes encountered, and to form a generalized picture of certain types of cloud systems involved. The emphasis here is on the interaction *between liquid and solid particles in the clouds* which result in precipitation at the ground; thus, formation of the clouds necessary for precipitation is not considered. Rather, this discussion concerns the fairly well known basic precipitation processes, such as natural seeding, diffusion, coalescence, aggregation, and accretion, as they apply to the inflight observations, and emphasizes some of the precipitation complexes that seemed to be typical of the temperate latitude storm systems that occurred in western Washington during the course of the test program.

Due to the great amount of time necessary for assembling and evaluating the many flight records and cloud sampling slides accumulated during the project operations, the inclusion of more than a sampling of the available quantitative data has not been possible. Hence this paper is necessarily of a preliminary nature and the conclusions are to a degree inferential.

2. PRECIPITATING CLOUD SYSTEMS

One of the more common precipitation complexes, observed to occur in the eastern portion of storms, involved a situation of multi-layered clouds, where ice crystals were generated in an upper layer consisting primarily of liquid cloud, and were falling through one or more lower-

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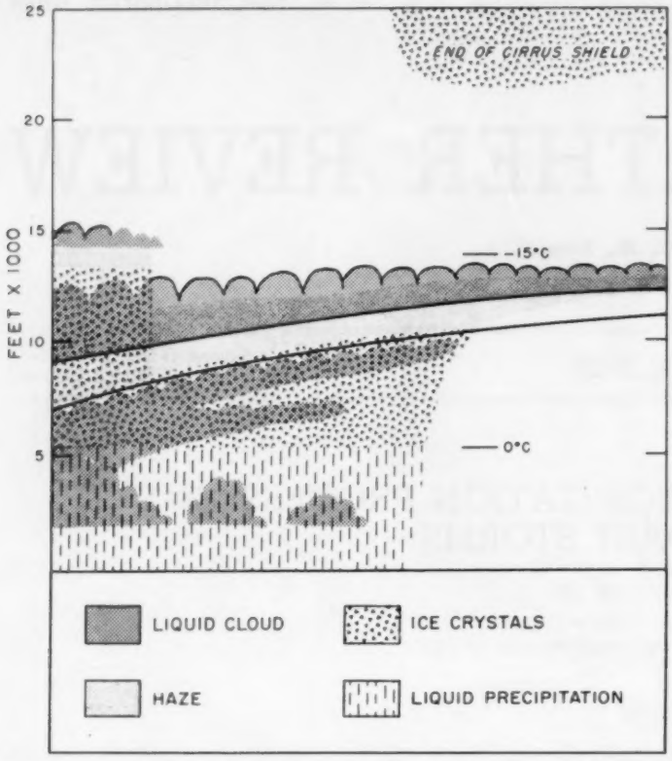

FIGURE 1.—Idealized cloud, frontal, and precipitation system found on the eastern side of winter storms in western Washington State. The types of cloud and precipitation elements involved are shown in the legend and apply also to figures 3 and 12.

FIGURE 2.—Top of a crystal-generating cloud such as was often observed during ACN Project flights. Altitude 12,000 feet; temperature −12° C. Some of the cumuliform domes are higher than the airplane.

level liquid cloud layers and air of high relative humidity. The top of the upper layer was usually at 12,000 feet or higher and the temperature ranged from −12° C. downward. The appearance of the top varied from that of stratocumulus to cumulus, but the cloud was continuous horizontally and contained indentations in the top sometimes as deep as 2,000 feet. Often there were no clouds above this layer. This sub-cooled liquid cloud provided a generating source of ice crystals with the result that descent beneath it often brought the airplane into an ice crystal environment. Just below this cloud deck, and in the upper portion of the precipitating ice crystal field, the crystals had the appearance of a haze, and were obviously small. At slightly lower elevations however, the crystals became visible as light colored streaks against the dark background of the wings and tail of the plane. At yet lower elevations, there were found one or more layers of low-density liquid cloud, into which the crystals fell and in which they appeared to grow rapidly. In the more intense storms, the water cloud could be found extending several thousand feet above, as well as some distance below, the melting level. It often appeared to develop upward, into the ice crystal field, until depletion by the falling crystals equaled the liquid being condensed. In and below the melting level, some of the precipitation elements grew into rain-sized drops [1], which further increased in size during passage through other liquid layers nearer the surface.

Figure 1 illustrates, in an idealized manner, the cloud and precipitation system in a rather stable configuration. Meteorological activity increases from right to left and the arrangement at the left is characteristic of the region just to the east of the cold front or occlusion. Figure 2 is a photograph of the top of a crystal-generating cloud such as would be found in the situation of figure 1. The altitude of the aircraft was 12,000 feet and the temperature was about −12° C.; surface precipitation downwind from the aircraft location was 0.01 to 0.02 inch per hour in the second hour following the observation. Presumably this was about the time when the observed cloud particles might have been contributing to surface precipitation.

Instability within certain layers caused a more unstable cloud and precipitating system as is shown in figure 3. In this instance the generating clouds are discrete elements but due to wind shear and particle size range, effective blanketing of the lower liquid clouds with ice crystals is accomplished. Figure 4 is a photograph of a smaller type of generating cloud sometimes found on the ACN flights. The tops in this case are estimated to be at 13,000 feet and at a temperature of −15° C.; precipitation at the surface downwind from the location of the observation and in the second hour following amounted to 0.01 to 0.02 inch per hour. Much larger generating clouds were encountered but were difficult to detect and photograph from the aircraft because of their size. They were detected, however, by the vertically-pointing TPQ–6 cloud-detector radar which was situated near the flight area at Hoquiam, Wash. The radar recorded a time section of these generating clouds and their resulting precipitation; a one-hour portion of an operational record is reproduced in figure 5 showing some high-level generating cloud areas with precipitation falling from them. In the illustration each horizontal line represents 5,000 feet in elevation, and the top of the highest echo is near 22,000 feet at an estimated temperature of −35° C.

Of the complex precipitation processes in these cloud systems, crystal generation (nucleation) and natural seeding are the most easily detected. Growth of the falling ice crystals, presumably by the diffusion process,

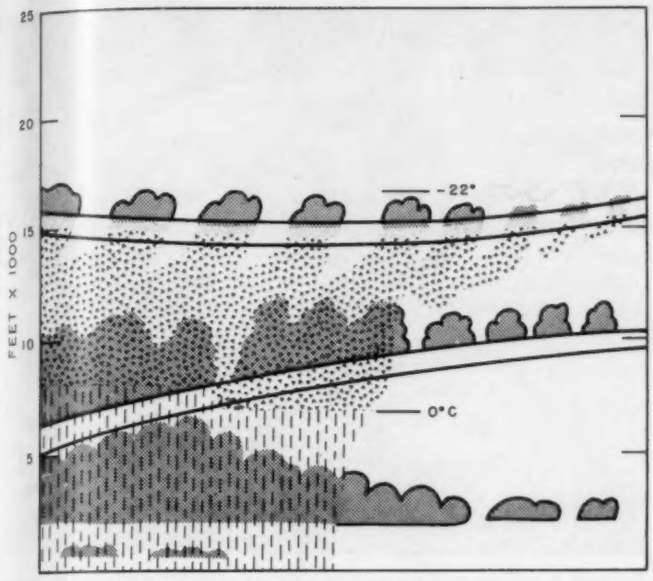

FIGURE 3.—Idealized cloud, frontal, and precipitation system where air layers are unstable. Wind shear and wide range of ice crystal sizes provide blanket seeding of the lower liquid clouds.

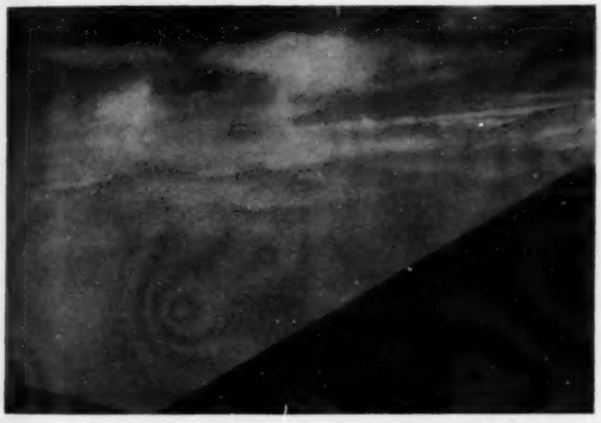

FIGURE 4.—Small generating clouds sometimes found above the general cloud deck. Altitude 13,000 feet; temperature −15° C. Streamers of ice crystals can be seen falling from them.

both above the liquid lower deck and within it was observed, and evidence of both coalescence of cloud droplets and aggregation of separate ice crystals was obtained.

3. DIFFUSION

The growth of ice crystals by diffusion is, of course, the process whereby the embryo ice crystal gains mass by incorporating water-vapor molecules into its crystalline structure. For this process to proceed it is generally assumed that water vapor supersaturation with respect to ice must exist in the growth environment. The growth of ice crystals by diffusion was observed beneath the cold, generating clouds during many of the ACN flights, the initial haze just below the cloud base developing into easily visible particles, as mentioned above. Growth within a layer composed of crystals and liquid particles was rapid, and beneath such a layer crystals were large and the crystal field was quite dense.

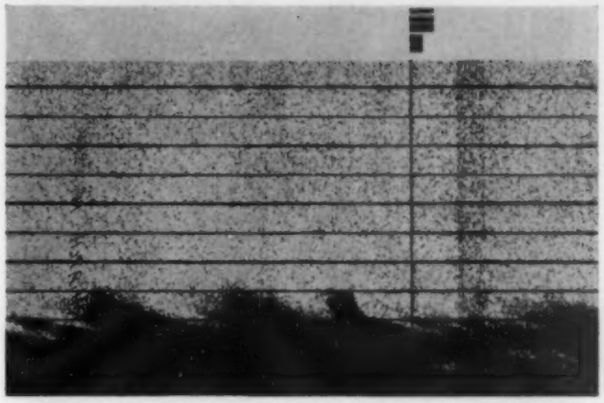

FIGURE 5.—One-hour sample record of vertically-pointing cloud-detector radar. Each horizontal line represents 5,000 feet elevation. Top of the highest echo is about 22,000 feet; temperature there about −35° C.

It is not, of course, to be assumed that diffusion alone caused growth of the ice crystals within the liquid-particle cloud; undoubtedly accretion took place but certainly the higher supersaturation over ice prevailing within the sub-cooled cloud would allow the component of growth by diffusion to proceed at a high rate.

4. COALESCENCE

Coalescence, the process by which one liquid droplet captures another, undoubtedly occurs in the cloud systems of western Washington and accounts for some of the precipitation falling there. Although coalescence cannot be observed from an aircraft flying through a cloud, cloud conditions favorable for its occurrence were often found. Figure 6, for example, shows a photomicrograph of impressions caused by the impact of cloud droplets on the magnesium-oxide coating of a sampling slide [2]. With the large droplets ranging from 100 to 200 microns in diameter and the smaller ones from 20 to 40 microns, terminal velocity ratios as high as 75 to 1 provided excellent coalescence conditions [3]. The sample was taken at 10,000 feet, −4° C., and in light icing conditions. Rainfall rates of 0.10 to 0.20 inch per hour were recorded downwind from the sample location in the second hour following its capture. Twenty minutes earlier the aircraft had descended from 13,000 feet to avoid icing, so it is probable that at the time the sample was collected, coalescence was taking place in more than 3,000 feet of liquid cloud. Conditions favoring coalescence, such as these, were encountered frequently during the flight operations.

On several flights drizzle-sized sub-cooled droplets were encountered by the airplane at relatively cold temperatures. One particularly interesting flight involved the attempt of the plane to top a very severe icing field. At the peak of the climb, at an elevation of 13,500 feet and a temperature of −10° C., a cloud sample was taken. Droplets captured ranged from 300 microns in diameter to about 10 microns, allowing fall velocity ratios of over 100 to 1. The droplet size distribution of

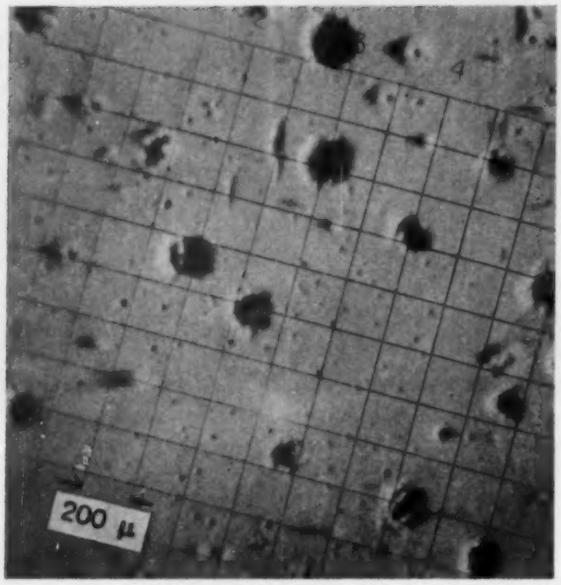

FIGURE 6.—Photomicrograph of impressions caused by impingement of cloud droplets on the magnesium-oxide coating of a cloud-sampling slide. The sample was taken at 10,000 feet and −4° C. in light icing conditions.

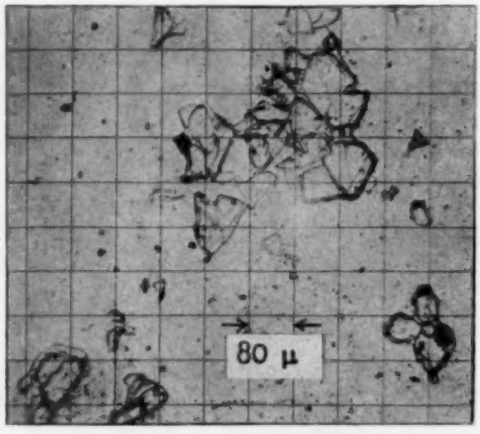

FIGURE 7.—Photomicrograph of formvar replica of aggregate of ice crystals. This sample was captured at 10,000 feet and −8° C., in a homogeneous-appearing and extensive ice crystal field.

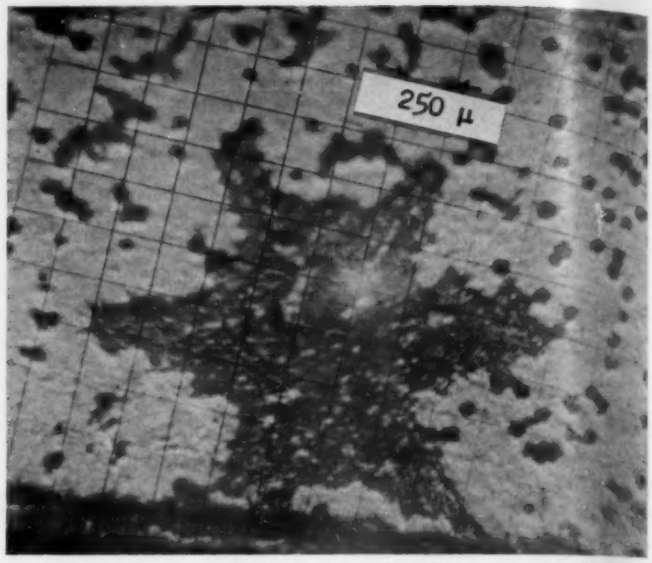

FIGURE 8.—Photomicrograph of imprint of 2000 μ diameter stellar crystal and numerous cloud droplets captured simultaneously on magnesium-oxide coated slide. Sampling conditions: altitude 10,000 feet and temperature −11° C.

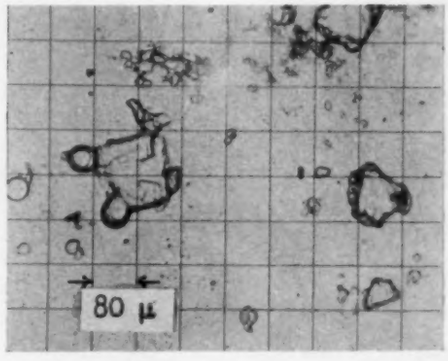

FIGURE 9.—Photomicrograph of formvar replica of atmospheric ice crystals and cloud droplets captured simultaneously. Note two droplets attached to a crystal. These were taken at 10,000 feet at −8° C. in a low-density ice crystal field in which liquid-cloud cells were imbedded.

the sample was bimodal having peaks at around 200 and 15 microns diameter. At the peak altitude the meteorologist reported that although the light intensity was high, he could not see through the cloud layer to blue sky and the sun was not visible; thus a considerable depth of cloud existed above the observation point. No ice crystals were seen in the vicinity of the airplane for some minutes before and after the time of this observation. It seems highly probable that coalescence was a contributing mechanism for the production of such large droplets. Such observations of large sub-cooled droplets are not too rare. Perkins and Kline [4] in 1951 submitted evidence of coalescence of liquid droplets in sub-cooled stratus clouds in the Great Lakes area. Under proper conditions sub-cooled liquid drizzle can even reach the ground as is shown by Kaplan's [5] report of freezing drizzle and rain over a wide area south of the Great Lakes from clouds whose temperatures were below freezing throughout. Coalescence very likely was the mechanism involved in the production of this sub-cooled liquid precipitation.

5. CRYSTAL AGGREGATION

The collision and aggregation of pre-existing ice crystals is also an important mechanism in these cloud systems. During the flights, many ice crystal samples were taken and very often aggregates of crystals were captured. One such aggregate is shown in figure 7, a photomicrograph of the crystal replica. Capture was at an altitude of 10,000 feet and a temperature of −8° C. in a homogeneous-appearing and extensive ice crystal field. In an area

estimated to catch precipitation elements from the vicinity of this sample, that is, downwind from the sample location and more than an hour later, rainfall amounts of 0.07 to 0.12 inch per hour were recorded. Jensen [6] has shown that the force necessary to cause cohesion between ice particles is very small, but once adhered several times that force is necessary to separate them if the temperature is not colder than about −12° C. The dense ice crystal field from which the sample was collected afforded excellent opportunity for collisions and the temperature, according to Jensen, was appropriate for a high degree of cohesion. Since the cloud conditions on this flight were typical of those on many flights, it seems logical to conclude that aggregation was a factor in much of the precipitation in the western Washington area.

It is possible that the cluster of crystals in the replica of figure 7 was not adhered before capture, but the conditions for aggregation were quite favorable (a rather dense crystal field and great interaction depth), and the cluster was in an area on the sampling slide containing a rather sparse covering, generally, of single crystals. For these reasons it is believed that the figure shows a natural cluster of ice crystals.

6. ACCRETION

The opportunity for accretion, that is, the capture of liquid droplets by falling ice crystals, was quite frequently observed. The airplane encountered liquid particles within ice crystal fields, often where the crystal field was most dense and the crystals largest. Two examples of conditions favoring accretion are shown in photomicrographs of cloud sample slides in figures 8 and 9. Figure 8 shows the imprint made on a magnesium-oxide slide by a 2000-micron diameter stellar crystal that was captured in a field of liquid droplets whose diameters ranged from 20 to 60 microns. These sizes provided fall velocity ratios between the crystals and droplets of as high as 150 to 1 [7, 8]. Capture was at an altitude of 10,000 feet and at a temperature of −11° C. This appeared to be a case of liquid cloud either forming at the flight level or building up from below. Moisture influx must have been at a high rate to allow condensation in the presence of a crystal field near the temperature of the maximum vapor pressure differential. Figure 9 is a photomicrograph of ice crystals and droplets captured together, and on one platelet fragment can be seen two small droplets. Capture was at 10,000 feet and −8° C. In this case the plane, while flying in a low-density ice crystal field, appeared to be encountering cells of liquid cloud some distance below their tops. At times, relatively small crystal-generating clouds could be observed several thousand feet above the airplane.

These illustrations do not, of course, provide conclusive evidence that accretion occurred in these cases, but it seems highly probable that the faster-falling stellar crystal may have been capturing liquid droplets and that the smaller platelet captured the two smaller droplets before their impact on the formvar-coated slide [9]. The fact that crystals and droplets, whose fall rates differed, were captured simultaneously certainly indicates that the opportunity for accretion was present.

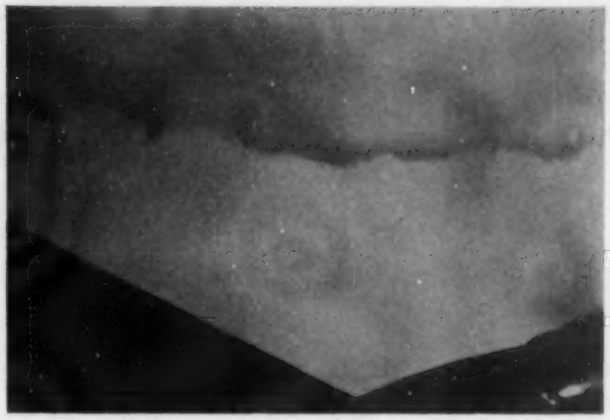

FIGURE 10.—Liquid-cloud-deck top being seeded naturally by higher-level ice crystal cloud. Aircraft altitude 15,000 feet; temperature −18° C. Note the soft, fuzzy appearance of the seeded cloud.

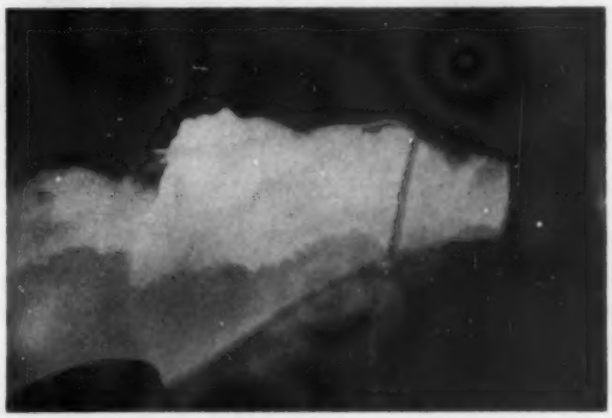

FIGURE 11.—Same cloud deck as in figure 10 but about 15 miles farther west beyond the influence of the upper seeding deck. Altitude and temperature were the same. Note the hard, bright cloud outlines and increased height of the deck.

7. NATURAL SEEDING

On one occasion it was possible to witness the direct effect of natural seeding on a liquid deck. The aircraft was cruising between two vaguely defined layers taking occasional light icing from the undulating top of the lower layer and encountering very small ice crystals falling from the upper deck. Eventually the end of the upper deck was reached but the lower deck extended on outward, and consequently one could observe the appearance of the lower deck both with and without the seeding crystals from the upper cloud. In the portion of the lower deck being seeded, the top was hazy and indefinite, and had a somewhat fuzzy appearance. Figure 10 is a photograph of the upper seeding deck and the lower seeded liquid deck taken from 15,000 feet, and at −18° C. Beyond the influence of the upper deck, in the unseeded portion of the cloud, the average level of the layer was somewhat higher and cumuliform domes were well defined and bright. Figure 11 shows the lower deck beyond the extent of the

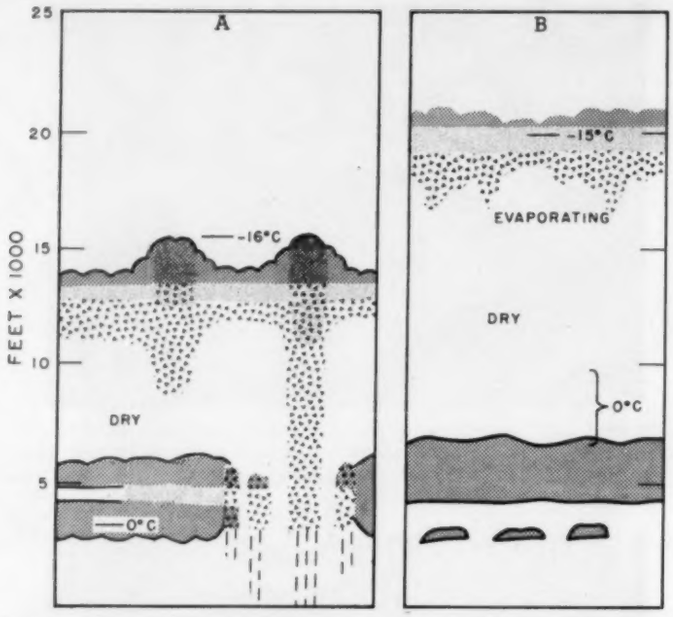

FIGURE 12.—(A) Idealized cloud and precipitation system sometimes found during mild meteorological activity. Seeding showers cut holes in the lower sub-cooled deck. (B) Idealized cloud system found during very light meteorological activity. Seeding particles evaporate before reaching the lower deck, hence there is no production of precipitation from it.

upper ice-crystal-producing deck, taken about five minutes later than figure 10 and at the same altitude. Natural seeding in this instance apparently depressed the top of the lower cloud deck and decreased the cloud density.

On another occasion natural seeding from an upper deck was in the form of scattered ice crystal showers, rather than a continuous ice crystal field. Whenever the showers reached the lower deck, they produced holes which often penetrated completely through the lower deck. Around the edges of the holes one could observe small snow showers continuing to fall, indicative of either the result of spreading of the seeding effect, or illustrating the fact that the seeding was less intense in the outer portion of the snow showers and took longer to develop. Figure 12A shows schematically the cloud deck and precipitation element arrangement just described; this occurred during mild meteorological activity.

8. NON-PRODUCTIVE CLOUD SYSTEMS

On some flights no interaction was apparent between upper and lower cloud layers. The cloud system arrangement usually observed is shown schematically in figure 12B. The dryness of the intervening air layer combined with the weak output of the generating layer prevented the delivery of seeding crystals to the low-level liquid deck. This condition was observed during periods of weak meteorological activity and was characterized by stable thermal stratification of the atmosphere.

9. CONCLUDING REMARKS

The cloud systems surveyed in western Washington exhibited an almost endless variety of structure, and no attempt has been made to present an all-inclusive picture of precipitation mechanisms. The ones described, however, were often observed and possibly are typical of those which occur most frequently, and are probably responsible for a large fraction of the precipitation falling in that area during the winter months. While these results are of a preliminary nature and the conclusions are to a degree inferential, the inflight observations of cloud systems and precipitation processes agree to a great extent with those ound in the eastern United States [10].

ACKNOWLEDGMENTS

The writer wishes to thank Messrs. Ferguson Hall and D. B. Kline for numerous helpful suggestions.

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CYCLONE TYPES AT 500 MB[1]

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ABSTRACT

Examples of three types of 500-mb. cyclone development, distinguished by the location of the cyclogenesis relative to the zonal velocity profile at 500 mb., are shown. Differences in the mean motion of all three cyclone types are shown to be statistically significant.

1. INTRODUCTION

In the course of an investigation into the statistical characteristics of cyclones at the 500-mb. level (Duquet and Spar [1]) it was observed that these cyclones could be classified into three types with statistically significant differences between the types in terms of their mean daily motions.

The cyclone types were distinguished by their original locations relative to the large-scale 500-mb. circulation. It was found that the zonal velocity profile at 500 mb. over a sector of the hemisphere could be used to separate the cyclones into three types which form north of, in, or south of the zone of maximum westerlies. Examples of each cyclone type, as well as of some subtypes, are described below.

The zonal velocity profile interacts with the cyclone development in a manner that depends on the cyclone type. The high-latitude (type I) cyclones, which form north of the maximum westerlies, contribute to an increase in the maximum westerlies. The low-latitude (type III) cyclones, which form south of the maximum westerlies, tend to diminish the west wind maximum and may produce a secondary maximum in lower latitudes, south of the Low. Such a development may represent the beginning of an "index cycle" in the form of a latitudinal shift of the zonal circulation. The effect of the middle-latitude (type II) cyclones, which form in the belt of maximum westerlies where the meridional thermal gradient is also usually a maximum at 500 mb., is to reduce the west wind maximum initially. However, the subsequent development of the velocity profile depends on whether the cyclone migrates northward or southward across the westerlies.

2. CYCLONE TYPES

The type I cyclone forms in high latitudes well north of the belt of maximum westerlies. Often these cyclones begin their existence in the Arctic Low itself, where they may drift for days about the North Pole. In the case illustrated in figure 1 the Low apparently originated well north of latitude 80° N. The low center then moved southward, and at 0300 GMT on April 25, 1956, the time of the map shown at the top of figure 1, had already reached latitude 64° N., west of Hudson Bay. Subsequently, as shown on the 0300 GMT maps in figure 1 for the next three days, the cyclone recurved and moved eastward.

The graphs accompanying the maps of figure 1 show the mean geostrophic zonal velocity profiles at 500 mb. over a sector 80° of longitude wide centered on the meridian of the Low. The geostrophic wind speeds were computed for overlapping 10° increments of latitude. The latitude of the cyclone is shown by the blacked-in circle. (Dashed unblacked circles in the later figures are used to denote the latitude of the incipient cyclone.) The cyclone remained north of the maximum westerlies during its entire existence. As it drifted southward, the maximum westerlies shifted toward the latitude of the cyclone and strengthened, mainly due to the contribution of the strong westerlies south of the Low. Although all type I cyclones first appear north of the maximum westerlies, not all of them exhibit the behavior shown here. In some cases the Low "breaks through" the westerlies and ends its existence south of the west wind maximum.

The type II cyclone develops in the strongly baroclinic region at 500 mb. which Palmén [2] has referred to as the 500-mb. frontal zone. These cyclones are also associated with cyclone developments at sea level. In fact many of them develop out of occluding frontal wave cyclones. This frontal zone is also the zone of maximum westerly wind. Thus type II cyclones appear first in the belt of strongest westerlies.

The appearance of a type II cyclone in the maximum westerlies distorts the velocity profile, sometimes producing a secondary maximum south of the Low. After

[1] The research reported in this paper was sponsored by the Office of Naval Research under Contract No. Nonr-285 (09). Reproduction in whole or in part for any purpose of the United States Government is permitted.

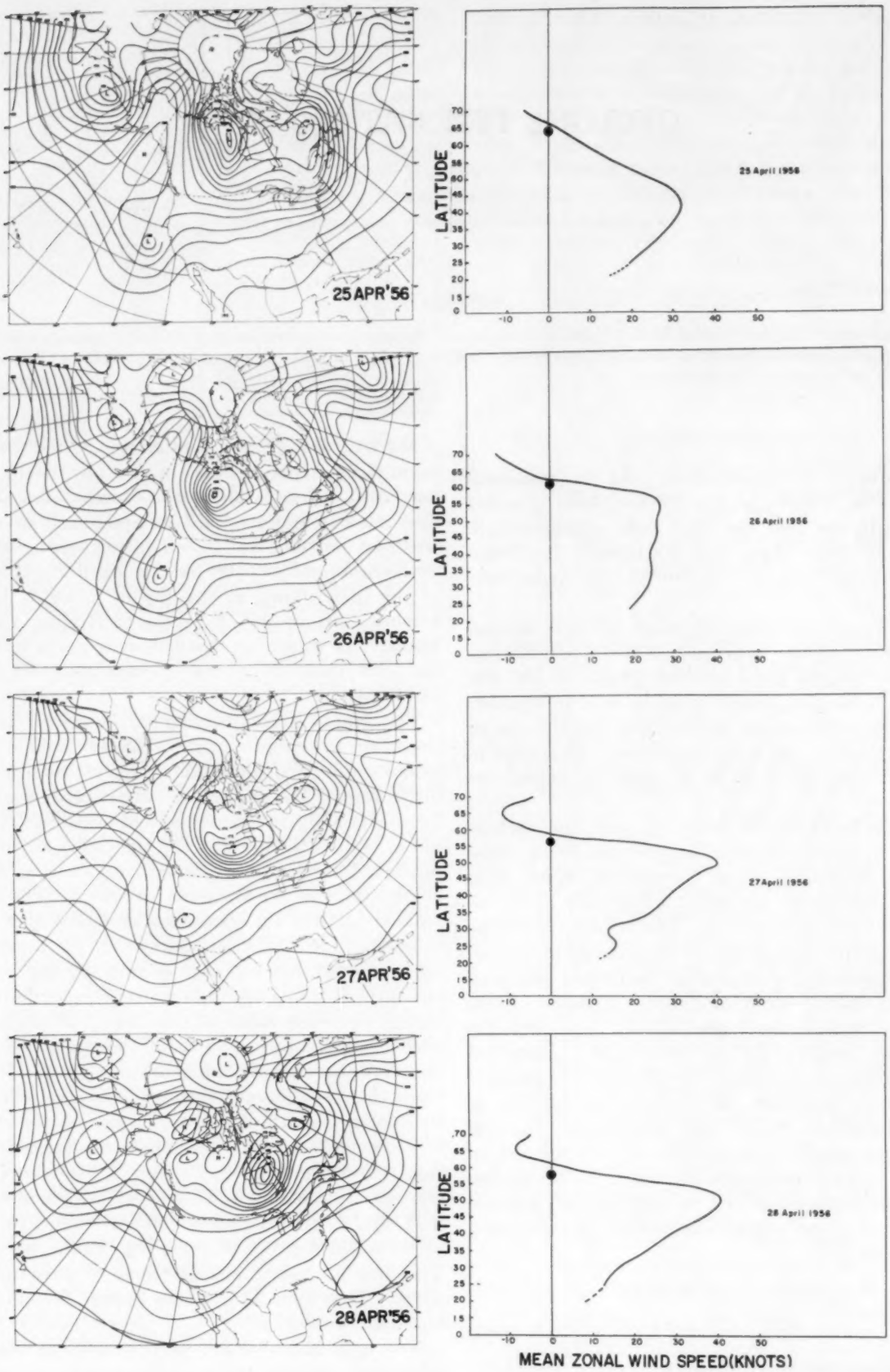

FIGURE 1.—Type I cyclone development at 500 mb., April 25–28, 1956. Geostrophic zonal velocity profiles on the right are computed for a sector 80° of longitude wide centered on the meridian of the cyclone. Black dot shows latitude of the cyclone.

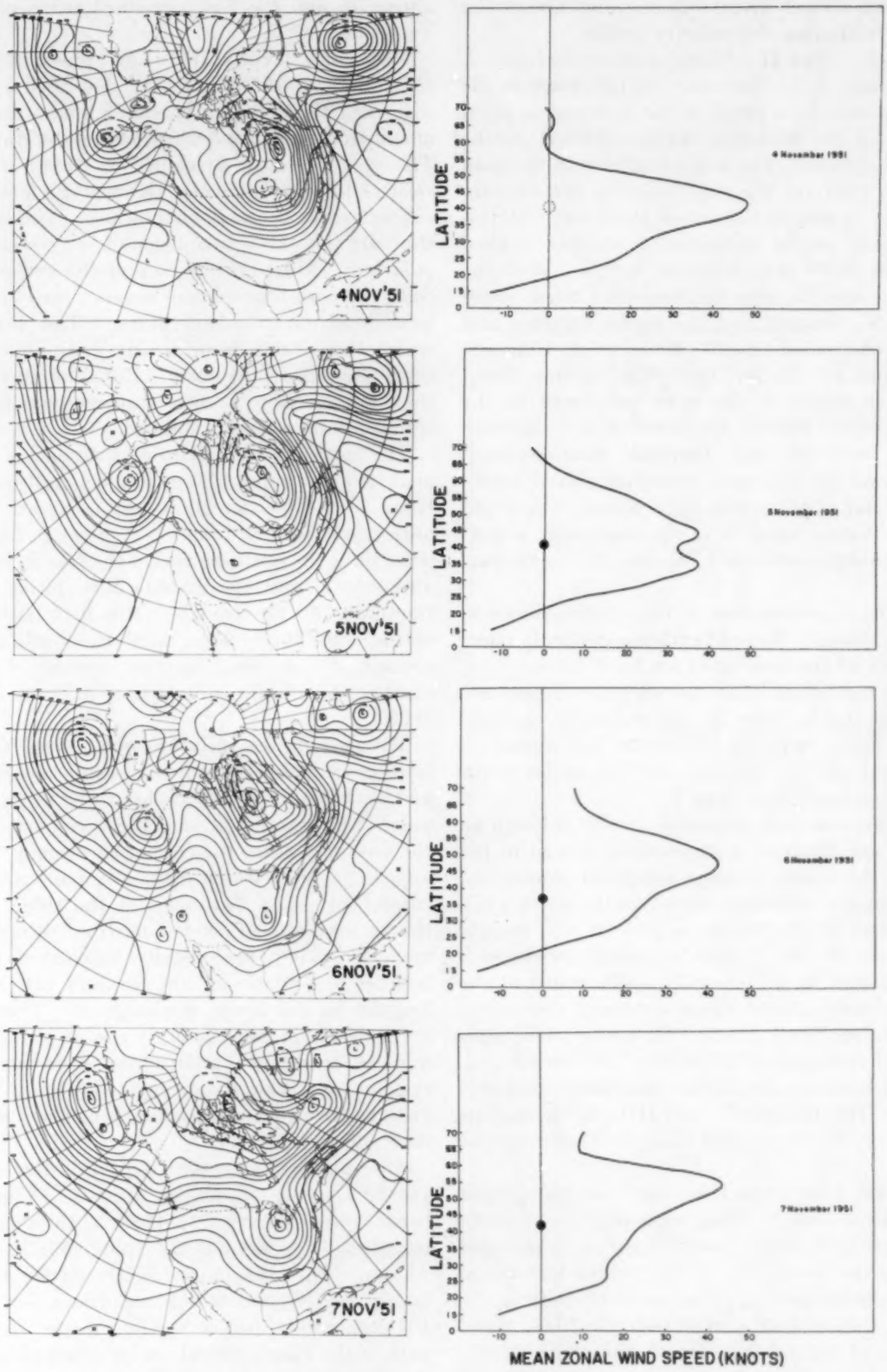

FIGURE 2.—Type II cyclone development at 500 mb., November 4–7, 1951. Dotted circle on velocity profile denotes latitude of incipient cyclone.

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it forms, the Low almost invariably migrates across the westerlies further altering the velocity profile.

An example of a type II cyclone is shown in figure 2. As in figure 1, each of the 1500 GMT 500-mb. maps in the series is accompanied by a graph of the geostrophic zonal velocity profile in the 80-degree sector centered on the meridian of the cyclone. The series begins with the map of November 4, 1951 (at the top), showing the 500-mb. circulation prior to the formation of the Low. At this time the velocity profile exhibited a sharply peaked maximum of 48 knots near latitutde 40° N. With the formation of the cyclone over the western United States at latitude 41° N., the next day, the profile flattened and the maximum decreased to 37 knots. (A Colorado cyclone developed on the sea level map at this time.) Subsequently, as shown in the next two maps of the series, the low center moved southeastward to latitude 37° N., then recurved and traveled northeastward. During this period the strongest westerlies moved northward. By the end of the series, the cyclone, which had first moved southward away from the maximum westerlies, was migrating northward across the maximum westerlies.

The high speed of propagation of the cyclone shown in figure 2 is quite typical. Type II cyclones generally move with the velocity of the associated sea level Lows.

It should be mentioned that not all type II cyclones form in exactly the latitude of the maximum sectoral westerlies. In many cases the low center first appears a few degrees north of this latitude, but not so far north that it can be confused with type I.

Type III cyclones almost invariably evolve through an increase in the amplitude of a pre-existent trough in the westerlies. As the trough become elongated toward the equator, the strongest westerlies remain in the north while the cyclone forms in the southern part of the trough. The development of the cyclone frequently produces a secondary maximum in the velocity profile south of the Low. In the early stages these cyclones are rarely associated with sea level Lows. However, they may induce sea level cyclogenesis after they have developed.

The type III cyclones can be further sub-divided into four sub-types; IIIa, the cutoff Low; IIIb, the kona type Low; IIIc, the blocking type; and IIId, the pressure pulse type.

Since the cutoff Low (type IIIa) has been the subject of several detailed case studies, especially by Palmén (loc. cit.), the example shown here in figure 3, is included merely to show the formation of the cyclone in relation to the zonal velocity profile. The series of daily maps, beginning with that of 0300 GMT January 2, 1947, shows the appearance of the cyclone far to the south of the latitude of maximum westerlies over the central United States. After the formation of the cyclone, the velocity profile exhibits the characteristic secondary maximum south of the Low. However, this feature later disappeared, and the Low remained south of the strongest westerlies.

The kona (type IIIb) Low illustrated in figure 4 (March 7–10, 1950) has been described by Simpson [3] who used this local Polynesian term to designate a kind of sub-tropical cyclone which affects the Hawaiian Islands. The cyclone shown developed on March 9 in the trough west of Lower California. Kona type 500-mb. Lows are characterized by weak circulations. Unlike cutoff Lows, they are not the consequence of large-scale outbreaks of polar air. Although the core of the cyclone is relatively cold, the core temperature is very nearly the same as the latitudinal mean temperature. The low latitude at which these Lows form clearly distinguishes them from those described previously. But, like all type III Lows, they too develop in the southern end of a long-wave trough of increasing amplitude.

The blocking (type IIIc) cyclone begins with a meridional trough approaching a blocking-type ridge. The block is most persistent in high latitudes where a closed anticyclone is often found. The trough line rotates eastward until the southern end of the trough lies south of the anticyclone, and the cyclone then forms by a kind of fracturing of the trough. The high-latitude block remains, while the cyclone, far to the south, drifts eastward around it. A blocking-type cyclone formation over southern California is illustrated in figure 5 (May 17–20, 1956).

The designation, pressure pulse type (type IIId), has been used to describe those cases of trough amplification and cyclogenesis which appear to be induced by pressure pulses which travel around the periphery of the ridge to the west and enter the rear of the trough. These pulses appear on the 500-mb. maps as minor troughs, or, sometimes, only as a flattening of the ridge. On vorticity charts they appear as fast-moving, secondary, vorticity maxima. They are usually associated with pools or tongues of cold air at 500 mb. and with warm pools or tongues in the lower stratosphere. They can be seen most clearly in the 12-hourly height change fields at 500 mb. as traveling katallohypsal systems. When these systems overtake the trough they may produce retrogression, trough amplification, secondary trough development, or cyclogenesis.

An example of a pressure pulse type development on the Pacific coast is shown in figure 6. This development began on February 21, 1953, with a small-amplitude trough moving around the split ridge over the Gulf of Alaska. The disturbance is shown by the dashed 12-hourly isallohypses which are drawn for an interval of 100 geopotential feet on the four maps. Arrows show the path of the katallohypsal center (marked with an F). As the disturbance reached the coast on the 22d, the ridge behind it re-established itself over the Gulf of Alaska.

The cyclone formed over the Pacific coast within the next 24 hours as the katallohypsal center moved south-

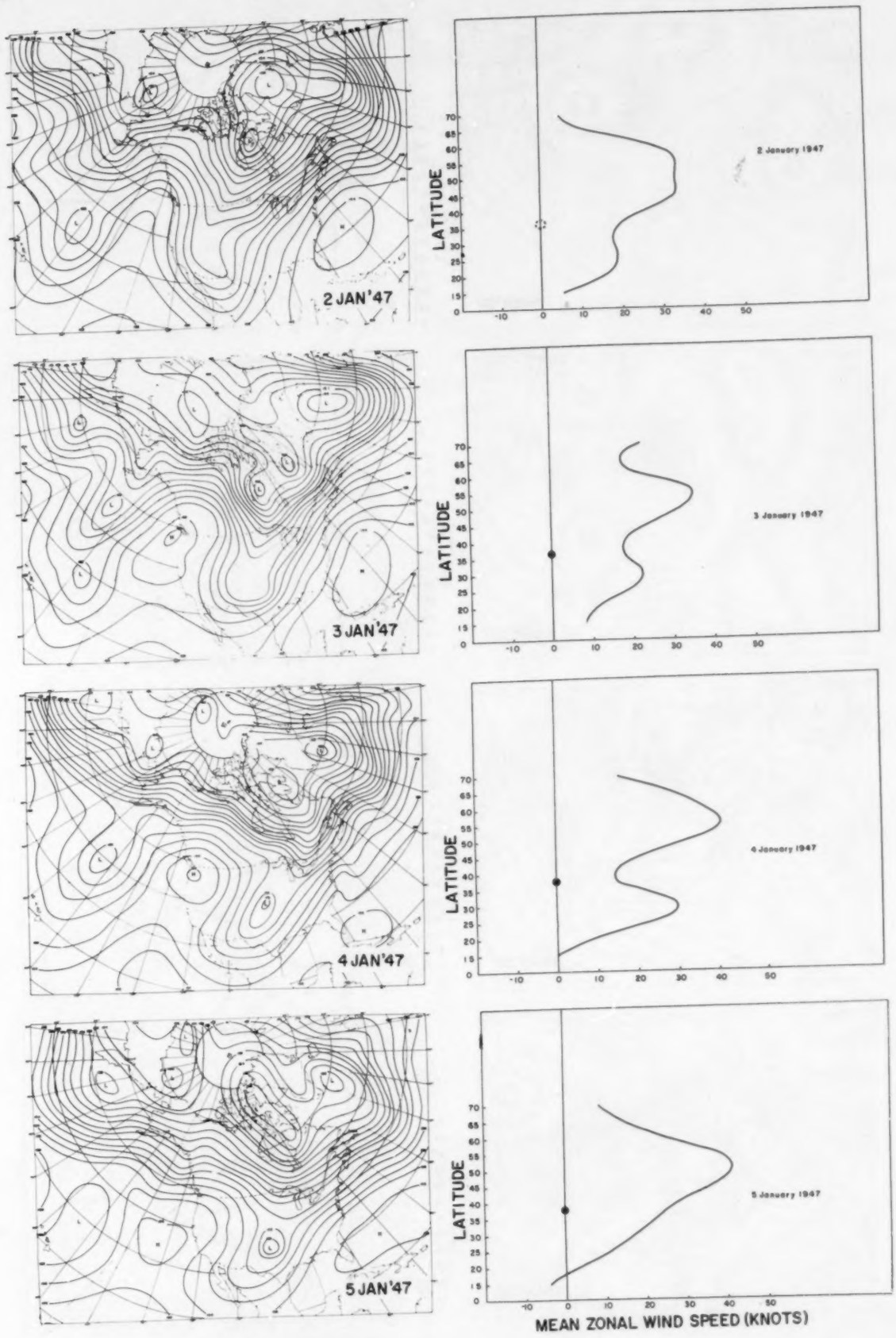

FIGURE 3.—Type IIIa (cutoff) cyclone development at 500 mb., January 2–5, 1947.

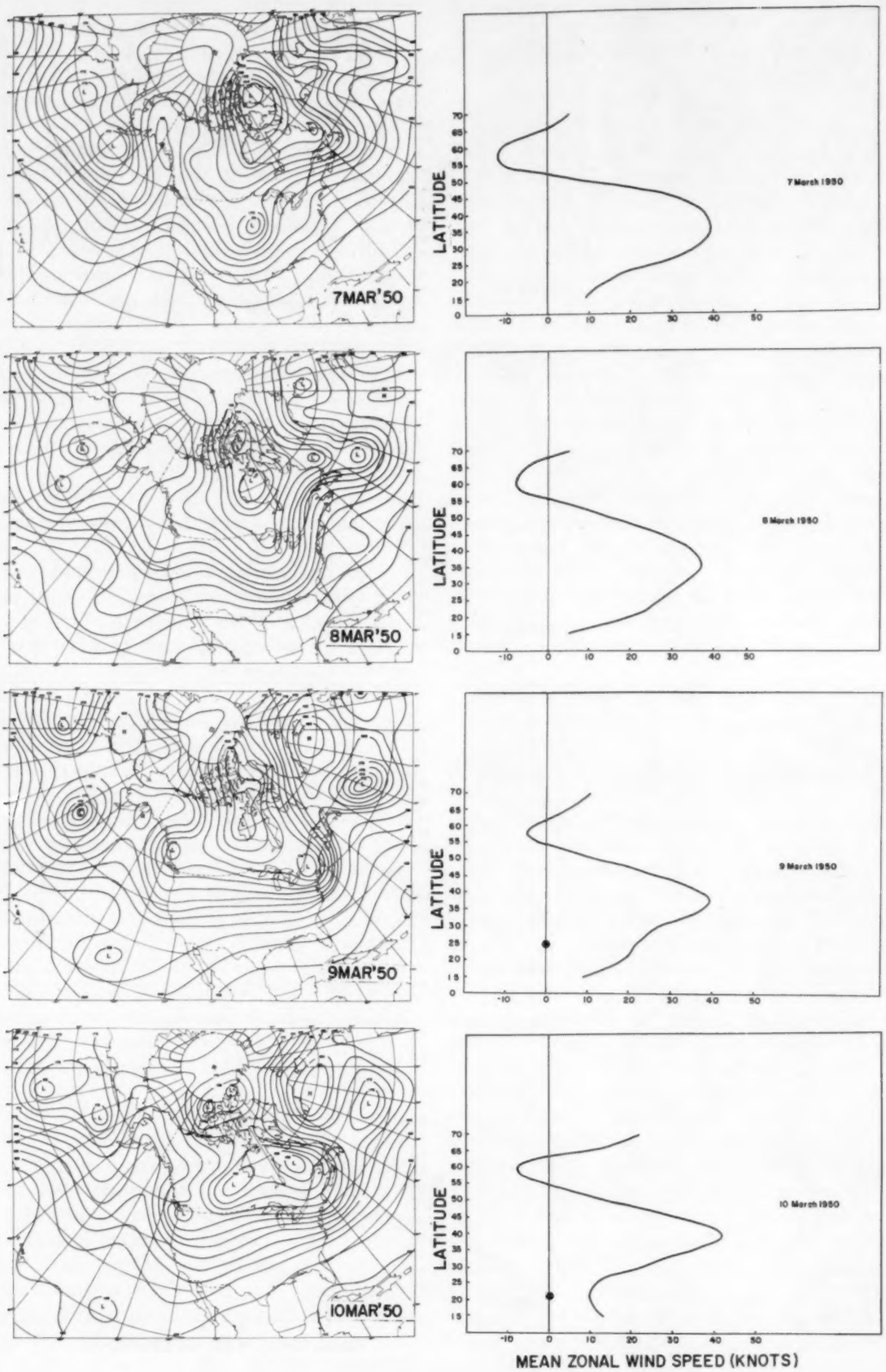

FIGURE 4.—Type IIIb (kona) cyclone development at 500 mb., March 7–10, 1950.

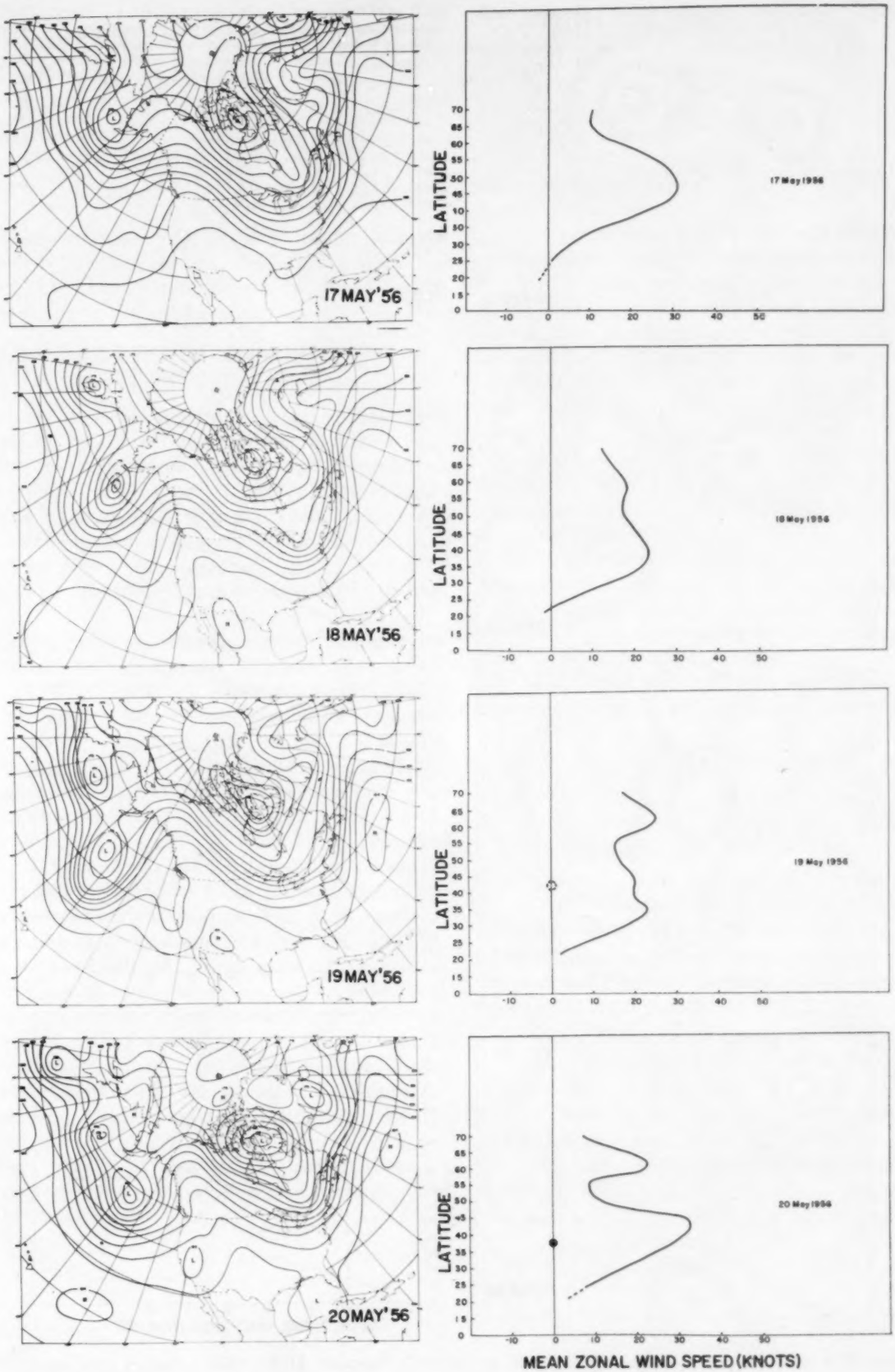

FIGURE 5.—Type IIIc (blocking) cyclone development at 500 mb., May 17–20, 1956.

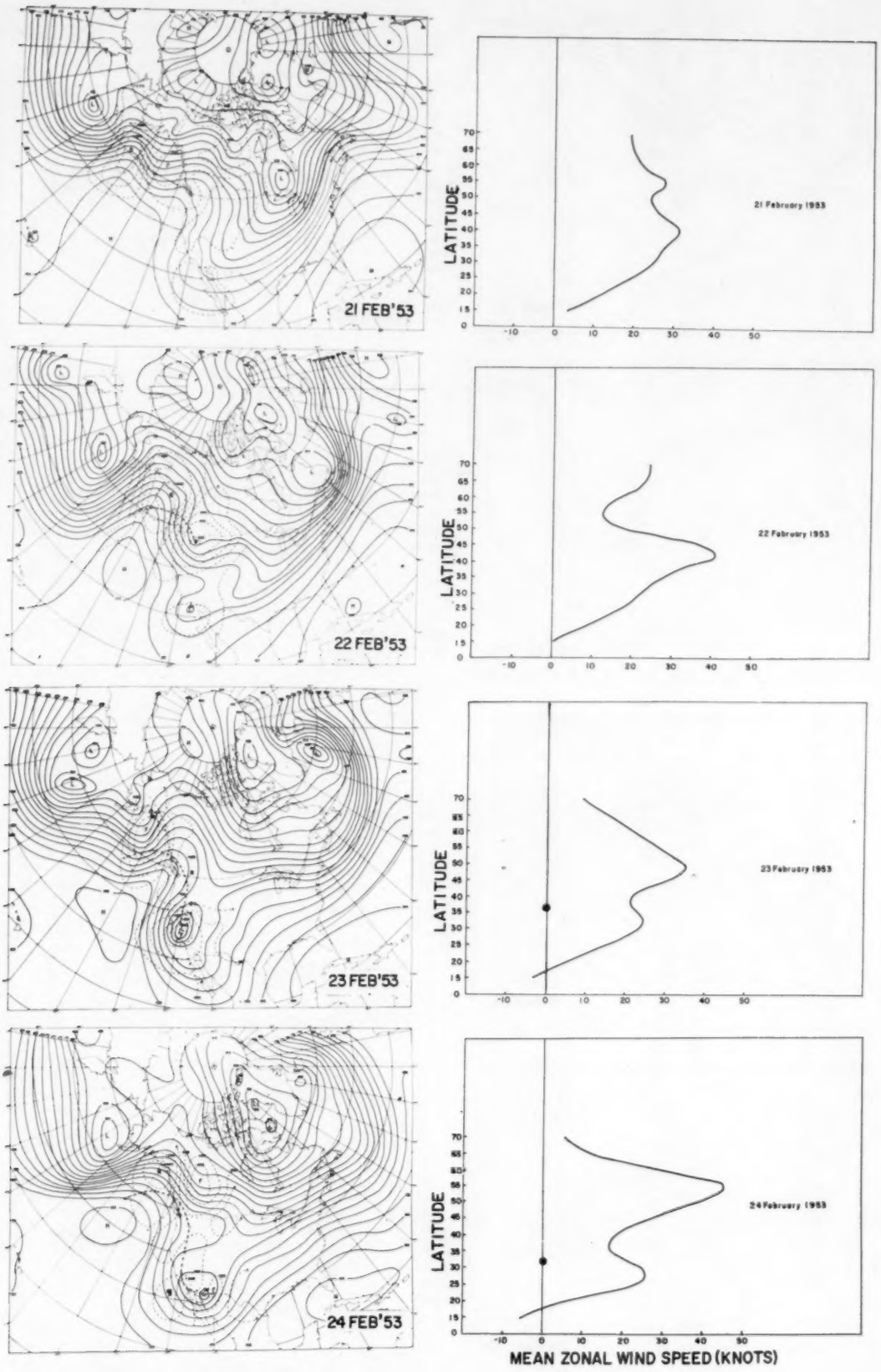

FIGURE 6.—Type IIId (pressure pulse) cyclone development at 500 mb., February 21–24, 1953. Dashed lines are 100-foot 12-hourly isallohypses. F denotes falling height, R rising height.

TABLE 1.—*Mean zonal (X) and meridional (Y) components of daily displacement of 500-mb. cyclones, according to type. Positive numbers denote displacements toward the east and north, negative numbers toward west and south. Units are degrees of latitude. S_x and S_y are the standard deviations. N is the number of cases.*

Cyclone Type	X	S_x	Y	S_y	N
I	4.0	6.0	−0.4	3.8	994
II	3.9	5.7	0.7	4.3	1108
III	1.4	4.6	1.0	3.6	850

ward. Subsequently the height-change center and the cyclone moved together toward the south. With the development of the Low, a secondary zonal velocity maximum appeared south of the cyclone.

3. MEAN DAILY DISPLACEMENTS OF THE CYCLONE TYPES

It is of some interest to determine if the cyclone types are distinguished by characteristics other than their locations relative to the maximum westerlies. Therefore a sample of 500-mb. cyclones was collected. The cyclones were classified into types I, II, or III, their 24-hour displacements were measured, and a statistical test was applied to determine if the differences among the mean displacements of the three types were statistically significant.

The sample included all 500-mb. cyclones in the region between latitudes 20° N. and 60° N. and longitudes 45° W. and 145° W. (the North American sector) which persisted for at least 24 hours during the period December 1, 1946 through November 30, 1952. Zonal and meridional components of the 24-hour displacements of the cyclones, expressed in units of degrees of latitude, were measured on the published daily 500-mb. maps for the period (Air Weather Service [4] and U. S. Weather Bureau [5]). A cyclone was defined as a height minimum enclosed by a 200-foot contour lying entirely within the sector described above. A total of 2952 daily displacements, rather evenly divided among types I, II, and III, were included in the sample. Since some of the centers persisted for more than one day, a single cyclone could contribute more than one displacement to the data.

The statistical results are shown in tables 1 and 2. Table 1 gives the mean daily zonal and meridional displacement components and their standard deviations for each cyclone type. Table 2 gives the "t" values for the differences between the displacements of the different cyclone types. The "t" values may be used to estimate the significance of these differences, if the displacements are normally distributed. (See, e. g., Brooks and Carruthers [6]).

TABLE 2.—*"t" values computed from data in table 1. (See e. g., Brooks and Carruthers [6].)*

Cyclone Types	X	Y
I–II	0.2	6.1
I–III	10.1	8.3
II–III	10.4	2.0

Note: "t" values in excess of 1.96, 2.58 and 3.29 are significant at the 0.05, 0.01, and 0.001 probability levels, respectively.

The high-latitude type I and middle-latitude type II cyclones have almost identical mean zonal displacements, and the "t" value for the difference between the two is not statistically significant. However, the type II cyclones have a mean northward displacement, while type I Lows have a mean displacement toward the south. The "t" value for this difference in the meridional component is highly significant. (The probability that the difference is due to chance is less than 0.001.)

Type III cyclones exhibit a slower drift toward the east than either type I or II. The difference between the mean zonal displacement of type III cyclones and that of the other types is highly significant. The difference between the mean meridional displacement of type III cyclones and that of type II is just barely significant at the 5 percent level. On the other hand, type III and type I Lows differ very significantly in their mean meridional displacements, according to table 2.

It is apparent that statistically significant differences in the mean motion of all three cyclone types do exist.

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6. C. E. P. Brooks, and N. Carruthers, *Handbook of Statistical Methods in Meteorology*, H. M. Stationery Office, London, 1953.

HURRICANE SEASON OF 1956

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1. GENERAL SUMMARY

The 1956 hurricane season was comparatively mild from the standpoint of storm frequency. Only eight tropical storms developed compared to an average during the past two decades of ten; four reached hurricane intensity compared to a normal of five during recent years. In only two of the past 15 years have tropical storms been so few and, by 1925 standards of detection and classification, possibly only three storms would have been designated as tropical. Two storms reached the coastline of the United States, both in the Gulf of Mexico.

The 1956 season was also mild from the standpoint of tropical storm intensity. One of the storms was of hurricane intensity for only a few hours, Flossy was of full hurricane intensity no more than 24 hours, and hurricane Greta was as much extratropical as tropical during her lifetime. Indeed only Betsy appeared to have all the characteristics of the classical hurricane and even this storm did not increase in intensity and size in accordance with statistical expectancy. None of the four hurricanes of 1956 could be classified as severe (120 to 150 knots sustained wind).

Tracks of the tropical storms of 1956 are shown in figure 1 and death and damage data are tabulated in table 1.

TABLE 1.—*Damage and deaths from all tropical storms and disturbances of 1956*

Type of storm	Date	Damage	Deaths*	Area
Tropical storm	June 13	$50,000	4	La., Miss.
Hurricane Anna	July 26	50,000	0	Tampico, Mex.
Hurricane Betsy	Aug. 11	10,000,000	18	French West Indies.
	" 12	25,500,000	9	Puerto Rico.
	" 13	380,000	0	Bahamas.
Tropical storm Dora	Sept. 12	Minor	27	Mexico.
Hurricane Flossy	" 24–25	24,774,000	15	Mostly in La., Miss., Ala., Fla.
Hurricane Greta	Nov. 1–4	1,680,605	0	Mostly Fla. east coast.
	" 3–5	1,899,201	1	Puerto Rico and other islands in Antilles.
Tropical disturbance	July 4–5	503,000	0	Alabama.
Quasi-tropical storm	Oct. 15–16	3,000,000	2	Florida.
Total in United States.		$30,007,605	19	
Total Atlantic hurricane area.		$67,836,806	76	

*Zero indicates no deaths reported.

2. INDIVIDUAL STORMS

Unnamed Tropical Storm, June 11–14.—This was the second tropical storm to occur in June in 10 years. On June 9, a fracture occurred in the polar trough lying just off the Atlantic coast, and the southern section began moving westward across Florida into the Gulf of Mexico while the northern section continued eastward over the western Atlantic. The westward moving southern section apparently induced an easterly wave which moved across the extreme western Caribbean, western Cuba, southern Florida, and the Yucatan Peninsula, and on the 12th formed a depression in the Bay of Campeche under the mid-tropospheric trough. The disturbance moved northward, acquiring tropical storm intensity and the center crossed the Louisiana coast a short distance west of Grand Isle during the late forenoon of the 13th. According to the report from the hurricane forecast center at New Orleans, "The storm had both tropical and extratropical characteristics. Rainfall was tropical in nature but never formed in bands characteristic of tropical storms and there was never any definite center or eye. The temperature aloft over the surface Low remained as cold or colder than the surrounding air." The situation in the high troposphere was also markedly different from that usually observed during hurricane formation. At 250 mb., at 0300 GMT on the 12th, an intense cyclonic circulation was centered southeast of Fort Worth and at 0300 GMT on the 14th this center had moved almost over the tropical storm in Louisiana.

The highest wind reported ashore was 55 m. p. h. from the east at Grand Isle, at 0715 CST on the 13th. A boat 5 miles south of Pilottown, La., reported gusts to 60 m. p. h. from the south-southeast. The lowest observed pressure was 29.66 inches at Moissant Airport, New Orleans, and at McComb, Miss. The highest measured tide was 4.7 feet above mean sea level at Biloxi, Miss.

The heaviest rainfall was within 100 miles of and to the east of the storm track and decreased from 6.13 inches at Grand Isle, La., to 5.60 inches at Monticello, Miss., 3.17 inches at Jackson, Miss., and 1.60 inches at Greenwood, Miss. The benefit to crops from these rains, which ended a drought at least temporarily, exceeded property losses from wind and water on the coast.

Four persons were drowned, three of them when a tug sank off the Mississippi coast and the other, a truck driver, when his truck skidded on the bridge over Lake Pontchartrain and plunged into the lake. The bridge was damaged by the truck but more seriously by a loose barge. The total damage to the bridge was estimated at $12,000.

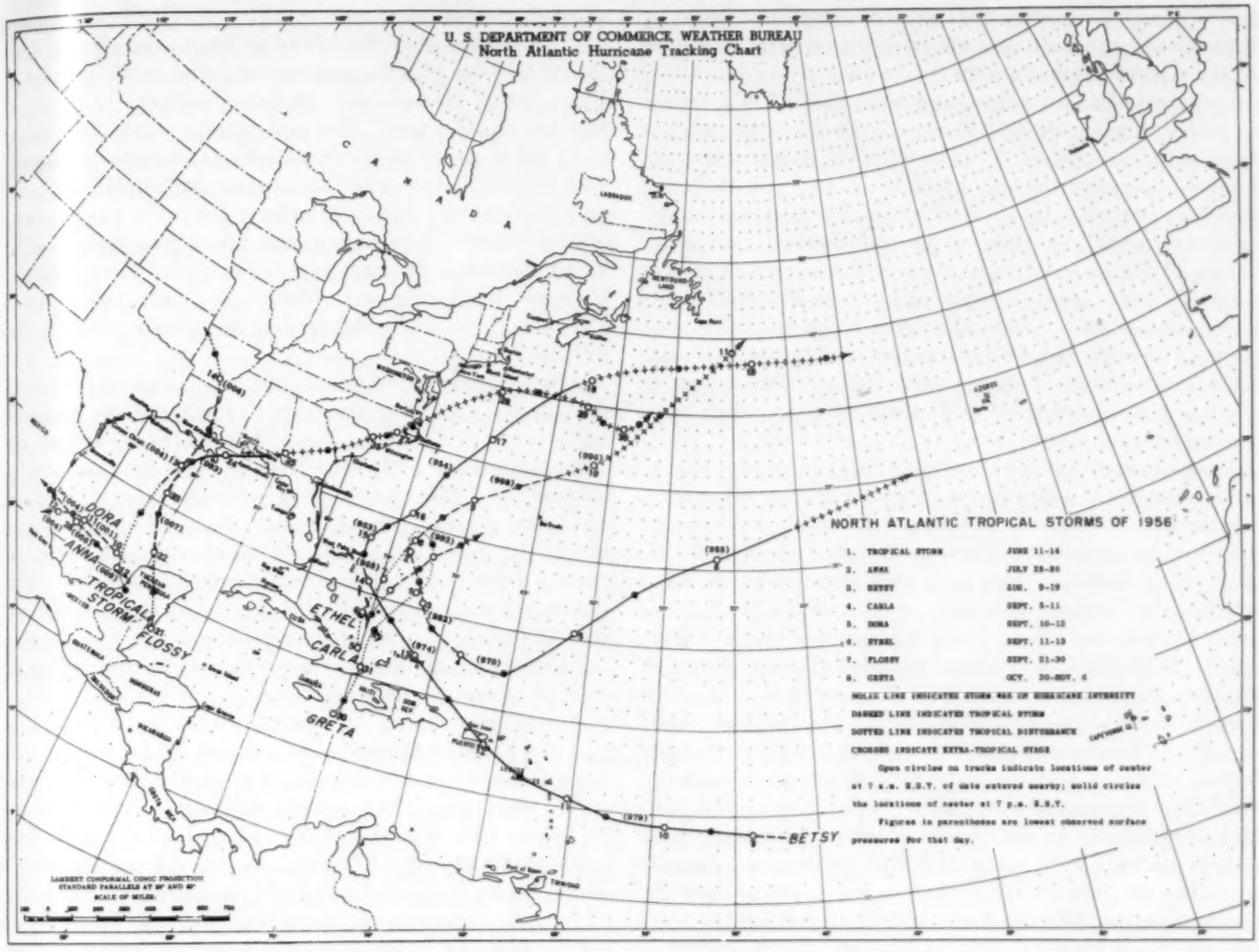
U. S. DEPARTMENT OF COMMERCE, WEATHER BUREAU
North Atlantic Hurricane Tracking Chart
NORTH ATLANTIC TROPICAL STORMS OF 1956
1. TROPICAL STORM JUNE 11-14
2. ANNA JULY 25-26
3. BETSY AUG. 9-19
4. CARLA SEPT. 5-11
5. DORA SEPT. 10-12
6. ETHEL SEPT. 11-13
7. FLOSSY SEPT. 21-30
8. GRETA OCT. 30-NOV. 6
SOLID LINE INDICATES STORM WAS OF HURRICANE INTENSITY
DASHED LINE INDICATES TROPICAL STORM
DOTTED LINE INDICATES TROPICAL DISTURBANCE
CROSSES INDICATE EXTRA-TROPICAL STAGE
Open circles on tracks indicate locations of center at 7 a.m. E.S.T. of date entered nearby; solid circles the locations of center at 7 p.m. E.S.T.
Figures in parentheses are lowest observed surface pressures for that day.
DORA
ANNA
TROPICAL STORM
FLOSSY
ETHEL
CARLA
GRETA
BETSY
LAMBERT CONFORMAL CONIC PROJECTION
STANDARD PARALLELS AT 20° AND 40°
SCALE OF MILES

FIGURE 1.—Tracks of hurricanes and tropical storms that occurred during 1956 in the North Atlantic Ocean.

Tides generally ranged from 1 to 4 feet above normal along the Louisiana and Mississippi coasts. The Freeport Sulphur Co. suffered some damage to their sulphur mines near the coast south of Houma, La., where the tide was 4.5 feet above mean sea level. Minor damage to the beaches, small boats, and piers occurred along the Mississippi coast in places where tides were said to have reached as much as 5 feet above mean sea level. The total damage from this storm is estimated at $50,000.

Hurricane Anna, July 25–26.—The easterly wave in which Anna developed passed through the Lesser Antilles on July 20 and continued westward through the Caribbean. Instability of the wave began to increase on the 23d as the wave, extending on the surface from central Cuba to Panama, passed under a very well developed anticyclone in the middle and upper troposphere. A weak circulation may have developed as it moved over the Yucatan Peninsula on the night of the 24th but all surface winds were under 20 m. p. h. Intensification was steady after the center passed into the Bay of Campeche and the depression intensified to storm intensity on the afternoon of the 25th.

On the morning of the 26th, Navy reconnaissance located the center with lowest pressure 991 mb. (29.26 in.) and found maximum winds of 50 knots in the northern semicircle. Early that evening the center moved inland south of Tampico, Mexico where a maximum wind of 70 knots (81 m. p. h.) was reported with lowest pressure 29.60 inches. It is thought that winds of hurricane force existed only for about three hours as the center approached and crossed the coastline.

Many houses in the poorer sections of Tampico were blown down and some roofs of the better homes were blown off. Although only 2.5 inches of rain were reported, downtown streets in Tampico were flooded. There were no reports of deaths or injuries. Damage has been estimated at around $50,000.

Hurricane Betsy, August 9–19.—The general circulation over the Atlantic during most of the hurricane season of 1956 and its possible relationship to the mild hurricane

activity will be discussed later. A temporary break in the prevailing circulation pattern occurred early in August as the Azores-Bermuda anticyclone moved northeastward for a period of about a week and intensified while a trough extended through western Europe. Similar patterns have been noted previously [1] as antecedent to hurricane formation. Apparently the injection of cold air aloft and cyclonic vorticity into the Tropics by a meridionally-extensive trough encourages the transformation of stable waves in the easterlies, and even in the intertropical convergence zone, into unstable waves and eventually into storm circulations. Around August 9, when the development of Betsy was first suspected, the anticyclone had reached maximum intensity and immediately began to subside and to return to its previous position south of its normal location.

Lack of reports in the eastern Atlantic makes it impossible to arrive at a detailed analysis for the period preceding the first indications of this storm but there was some evidence of an easterly wave near longitude 33° W. on August 6. Extrapolation at a normal rate of movement would have brought it to the vicinity of 50° W. on the 9th. On that date the following report was received from the *M/T Marisa:* "At 1218 GMT passed through trough of tropical storm in position 14.05° N., 55.25° W. At 1200 GMT 1008 mb., winds force 10, very high wild sea, heavy squalls." It was not possible to fit this report into any logical analysis and consequently efforts were made to verify the ship's position. At 1730 GMT a corrected position of 14.05° N., 49.05° W. was obtained. This was only a short distance from the routine Gull Papa reconnaissance track but the developing storm was too small to alert the reconnaissance observer and there was no diversion from the scheduled track.

A special reconnaisance flight was made on August 10, but confirmation of storm development was received through surface ship reports before the plane reached the area. The *M/S Sagoland* at 1200 GMT reported: "Lat. 14.35° N., Long. 54.10° W., at 0400 GMT, wind 035 degrees increasing force 5, barometer 1008 mb. At 0930 GMT northeast force 11/12, barometer 1004, violent sea, heavy rain, no visibility. At 1200 GMT wind east force 6, barometer 1009, heavy seas, rain, decreasing sea." The 1200 GMT observations from the *SS Mormac Lark* and *SS Willemstadt* on the outskirts of the storm, were also helpful in the location of the storm and evaluation of its intensity.

The first advisory was issued at 1100 EST, August 10, at which time a hurricane watch was advised for the Leeward and Windward Islands from Antigua to Barbados. When reconnaissance aircraft reached the storm later in the day, it was found to be a very small hurricane but with winds of 120 m. p. h. near the center and central pressure 979 mb. The eye was defined by a very tightly closed pattern on the radar as only 10 miles in diameter.

The hurricane moved on a west-northwest course at about 17 m. p. h. during the next 24 hours and passed through the central Lesser Antilles about midday August 11. It crossed over the island of Marie Galante and between Isle des Saintes and the extreme south portion of Basse Terre, Guadeloupe. Reports indicate 18 lives lost and severe damage. On Guadeloupe, 1,000 dwellings were extensively damaged, all communications disrupted, and 50 to 60 percent of the banana, breadfruit, coconut, and papaya trees destroyed, a serious blow to the economy of the island. The banana crop loss was estimated at $3.5 million and preliminary estimates give $10 million for the total damage figure. Winds were estimated at 100 to 120 m. p. h. on Guadeloupe and the lowest pressure was 991 mb.

After moving through the Leeward Islands, the hurricane began a more northwesterly course, passing about 30 miles south of St. Croix, Virgin Islands, and reaching the southeastern tip of Puerto Rico in the early morning of August 12. Prior to reaching Puerto Rico the storm displayed a small but apparently real oscillatory motion about the mean track with an amplitude of a little less than ½ degree and a period on the order of one day. The oscillation was sufficiently definite that some forecast use could be made of it, on an extrapolation basis. Following the turn to a more northwesterly direction, this oscillation was not present or was obscured.

A hurricane watch had been ordered for Puerto Rico and the Virgin Islands on the evening of August 10. As the hurricane continued to move toward Puerto Rico, the watch was changed to hurricane warnings on the afternoon of August 11. The eye of the storm crossed Puerto Rico between 1200 and 1530 GMT, August 12, on an erratic coarse [2] between northwest and west-northwest at about 17 m. p. h., emerging on the north coast near Camuy with only slight and temporary weakening of its circulation. According to reports, all of Puerto Rico, except the southwestern portion which was protected by the mountain backbone of the island, experienced winds of 75 m. p. h. or higher in gusts. Maximum sustained winds at San Juan were 73 m. p. h., with gusts to 92 m. p. h. Rainfall totalled 3.19 inches. Ramey Air Force Base, on the northeastern tip of the island, recorded wind gusts to 115 m. p. h. Nine deaths were reported in Puerto Rico and the property damage totalled $25,500,000 or more.

Hurricane Betsy continued at a speed of about 17 m. p. h. to near Turks Island early on August 13 and, with some acceleration, reached the vicinity of San Salvador in the Bahamas about 2000 EST on that date. Winds at San Salvador reached 132 m. p. h. in gusts. Sustained winds were 100 m. p. h. or more. Approximately 5 inches of rain fell in 5 hours. Several houses were demolished and most of the churches, which are generally better constructed, lost their roofs.

Aircraft reconnaissance on August 13 had shown a slight increase in size of the storm but little change in central pressure or maximum winds. Gale winds were reported as extending 125 miles north and 60 miles south of the center. Lack of important increase in size or

intensity was compatible with the fact that turbulence and rain in all quadrants were predominantly light with only intermittent bursts of heavy rain and moderate turbulence. On the 14th, central pressure was reported as 960 mb., the eye was 12 miles in diameter and well formed, and associated clouds extended 250 miles north and 200 miles to the east.

On August 14 and 15, Betsy began recurvature with sharp deceleration in forward movement. By the 16th it was moving toward the northeast and had increased its forward speed to about 20 m. p. h. Between the 13th, when the storm was near Turks Island, and the 16th, when a dropsonde was released in the eye near 30° N., 75° W., temperatures in the eye between the surface and 700 mb. fell about 2° C. The normal sea-surface temperature difference between these areas is less than 1° and, while some anomaly may have existed, it seems likely that the cooling was an indication of the beginning, even at this time, of some other factors interfering with the efficiency of the storm engine. By the 17th, a dropsonde in the eye showed that the cooling, by another 1° to 3° C., extended upward to almost the 500-mb. level. Maximum winds began to decrease on the 16th and by late August 17th had dropped to 80 m. p. h. Reconnaissance at this time reported the eye was becoming poorly defined as the hurricane moved northeastward at about 23 m. p. h. past the latitude of Nantucket. The last advisory was issued on the morning of August 18 as the storm assumed more extratropical characteristics. It moved due east on the 19th and 20th, gradually losing its identity.

The tracking and forecasting of hurricane Betsy was aided by the availability of more information in the form of air-borne and land-based radar observations and upper air soundings than in previous years. The storm successively came within range of radar at San Juan [2], the Air Force missile range stations in the Bahamas, and the Navy Hurricane Central at Miami. The AN/CPS–9 radar at the Navy Hurricane Central, Miami, established what possibly may be a record when hurricane Betsy was off the Florida coast on the 14th. The center of Betsy was initially detected by this radar at a range of 293 nautical miles and presented a perfect scope picture for the next 26 hours until she was lost at 269 nautical miles.

Aircraft reconnaissance by the Air Force and Navy was up to its usual high standards. Despite all this, Betsy was not without forecasting problems. The most difficult problem, as it usually is, was the recurvature. From the time of inception until August 13, the movement was consistent and could be forecast with a high degree of confidence. However, on that date the center was approaching an area where recurvature appeared to be a likely possibility on the basis of climatology, and a slight possibility on the basis of the prevailing circulation. From the standpoint of public warnings, the problem was further complicated by the relatively rapid movement of 18 m. p. h. (during certain short periods on this date it appeared to move as fast as 25 m. p. h.) and the time-of-day factor. At 1700 EST, on the 13th, it was decided that with the rate of advance and the direction and speed of movement indicated by the Riehl-Haggard [3] technique, which gave excellent results on the whole with this storm, squalliness could develop on the Florida southeast coast on the forenoon of August 14. If hurricane warnings were delayed until the next morning, and the forecast track verified, insufficient time would remain for adequate preparations. Consequently, hurricane warnings were issued for a portion of the Florida east coast. The underlying reasons for the action, and the degree of uncertainty attached to a hurricane forecast for such a period of time, were expressed in the public advisory. By the morning of August 14 stronger evidence in favor of a northward turn was appearing, and later in the day all hurricane warnings were lowered. However, there remained another 24 hours of slow movement during the recurvature process before all threat to the United States coast had definitely passed.

At 500 mb., during the early history of Betsy, a trough extended from Newfoundland to near Bermuda. The southern portion of this trough tended to fill as Betsy moved past, and heights in the area of an anticyclone along the southeastern United States coast had been rising for some time when the storm reached the area of Turks Island on August 13. This, with other factors, created some doubt as to whether recurvature could occur east of Florida. The long-wave pattern at this time was becoming poorly defined and of small amplitude, with indications that a trough should develop in the Great Lakes region, permitting the High along the southeastern coast to persist and hamper recurvature. It was not until the 14th that developments, including the weakening of the High over the southeastern coast, began to favor the northward turn.

The accepted movement-forecast techniques were applied and were found useful to varying degrees. None were without failures at some stage, particularly during recurvature. Three 24-hour forecasts obtained by the Riehl-Haggard technique were within 17 miles, which is as close as the center can usually be located at sea. However, passage of the storm through the network of upper-air stations at Air Force missile bases and on islands to the south permitted the collection of data which may prove helpful in analyzing some of these deficiencies in our present knowledge of hurricane behavior. This is especially true of the upper troposphere, for which we have previously had severely limited data.

There were at least 27 deaths connected with Betsy, and total damage in monetary terms, including an estimate of $380,000 in the Bahamas and a few other islands, appears to be around $35,880,000.

Tropical Storm Carla, September 5–11.—The first indication of Carla appeared on September 5 when a weak circulation showed up in an easterly wave which was moving into the southeastern Bahamas. During the next several days it moved on a parabolic course and on the

7th recurved northeastward with some deepening and the area of strong winds expanded to cover an area 300 to 400 miles in diameter.

A strong southeastward outbreak of polar air was taking place in the eastern and central United States and the accompanying cold front passed off the east coast during the morning of the 7th. On the 8th interaction between the High with central pressure 1034 mb. over the Lakes Region and the tropical Low off the southeastern United States coast was causing strong northeast winds from the central Florida coast northeastward along and off the Georgia and Carolina coasts. Gales spread to the New England coast as the Low moved to a position near Lat. 32.5° N., Long. 70° W. by the morning of the 9th. Reconnaissance aircraft on the morning of the 9th located an ill-defined center but reported no eye existed and no spiral bands were in evidence. Highest surface winds near the center were estimated at 30 knots. However, 40 to 50 m. p. h. winds were found extending 200 miles to the west and northwest and 40 m. p. h. winds some distance to the east and south. During the period of greatest intensity, the storm was probably not a true tropical storm. It had definitely taken on extratropical characteristics by the forenoon of the 10th and only three advisories were issued.

On the morning of September 5, when the weak easterly wave extended northeast-southwest through the southwestern Bahamas, a weak trough or shearline existed in this area at all levels to 500 mb., with a deep Low at 300 mb., about 700 miles to the northeast near Lat. 26.5° N., Long. 62.5° W. During the next two days this 200-mb. Low seemed to split, with one section moving off to the northeast and the other drifting southwestward over Cuba into the northwestern Caribbean and over the Yucatan Peninsula by the evening of the 8th. At about this same time, the polar trough at the mid-troposphere was moving off the coast of the southeastern States and deepening, and by the morning of the 10th, Carla, now almost entirely surrounded by cool air at lower levels, was pulled into the trough and carried rapidly out over the Atlantic to the northeast.

Thus it may be seen that during the formative stage of Carla, it was never in a favorable location with respect to the 200-mb. high pressure cell to augment deepening.

Tropical Storm Dora, September 10–12.—A tropical storm formed during the afternoon of September 11 in the southwestern Gulf of Mexico in a depression that had been drifting westward. Navy reconnaissance during the previous afternoon found a rather large area in the Bay of Campeche with scattered squalls. The lowest pressure was 1010 mb. and the maximum wind 35 knots.

On the 11th, aircraft reconnaissance found the lowest pressure to be 1004 mb. and the maximum wind 65 knots. This storm has not been classified as a hurricane since the 65-knot wind was an estimate and not a measurement, and it is not believed that the required pressure gradient for this speed existed. The next morning the minimum pressure was the same and maximum winds were 50 knots. The center moved inland around noon near Tuxpan, Mexico with lowest pressure 1002 mb. and highest wind 30 knots.

The New Orleans forecast center reported that heavy rains in Mexico caused a landslide in which 13 persons in a bus were killed and these deaths were attributed to the storm. Some flooding occurred from the heavy rains, but damage is believed to have been slight. A later news dispatch said, "The death toll from after-effects of Mexico's short lived Hurricane Dora rose to 27 today with reports of 7 persons drowned in the overflowing Pachuapan River near San Andrés Tuxtla."

At 200 mb. the storm remained south of, and about midway between, a High centered over Texas and a trough over the eastern Gulf—not a very favorable location for rapid intensification.

Tropical Storm Ethel, September 11–13.—At 1330 EST September 11, a weak circulation was noted over Great Exuma Island in the Bahamas, about 100 miles south of a quasi-stationary front. During the next 24 hours the tropical depression moved north-northeastward and gradually intensified. On the afternoon of the 12th, research aircraft reconnaissance entered the storm and found a well-developed eye about 20 miles in diameter and entirely surrounded by a typical wall cloud extending upward about 30,000 feet. A maximum wind of 66 knots was encountered while entering the eye over a distance of some 3 miles in the northeastern quadrant. Thirty-knot winds extended outward 30 to 100 miles in all directions but no hurricane winds were found in any other quadrant.

By late on the 13th, the storm had assumed extratropical characteristics and lost intensity. It is thought that the storm may have developed strongly for a short time as a new source of energy in the form of cold air entered the system. Since development took place under a broad polar trough, even this much intensification was surprising. If the research plane had not flown into the storm on the 12th, no advisories would have been issued and it would not have been listed as a tropical storm.

Hurricane Flossy, September 21–30.—The origin of this hurricane—the only one to reach the coast of the United States in 1956—is rather obscure. Hurricane squalls were reported in the Pacific south of Guatemala on the 20th, and the initial impulse may have moved northward from there or from the Caribbean. The first well-developed circulation was noted over the Yucatan Peninsula at 1330 EST on the 21st, passing into the Gulf of Mexico near Merida. According to the report of the hurricane forecast center at New Orleans, the circulation intensified gradually while moving northward over the Gulf and reached storm intensity on the afternoon of the 22d. After this time the size of the storm increased considerably but the pressure gradient around the center intensified only slowly. The tropical storm reached hurricane force near or somewhat before noon on the 23d

when the center was about 125 miles off the southeastern Louisiana coast.

During the afternoon the hurricane turned rather sharply toward the east-northeast, crossing the Mississippi delta a little north of Burrwood near Pilottown early on the 24th. Here it seems to have reached maximum intensity with highest wind at Burrwood 84 m. p. h. and lowest pressure 29.03 inches. An oil rig a little west of Grande Isle reported a maximum wind of 83 m. p. h. and gusts to 95. The New Orleans forecast center attributes the turn to the east-northeast to "the central core of the hurricane building upward and reaching into the westerlies." This change in direction was also indicated by the Riehl-Haggard forecasting technique. The center passed a little south of Pensacola, Fla., during the afternoon and later about over Fort Walton. The storm became extratropical shortly after the center passed out of Florida but it moved northeastward inside the coastline as an energetic storm until it passed out to sea near the Virginia Capes.

As far as known, no hurricane winds were reported at any Florida point although winds were near hurricane force eastward along the coast to Panama City. The lowest pressure reported during the storm was 28.93 inches at the Pensacola Naval Air Station. The highest storm tide was 7.4 feet m. s. l. at Laguna Beach, Fla. Some higher values were reported along the eastern side of the Mississippi delta but have not been verified. Tides flooded portions of Norfolk, Va., and water stood 2.5 feet deep in several of the principal streets. Beach erosion occurred as far north as Delaware.

The heaviest rainfall reported was 16.70 inches at Golden Meadow, La., and 16.30 inches at Gulf Shores, Ala. The rainfall intensity decreased gradually as the storm moved northeastward but 1 to 3 inches fell as far north as Virginia. Three tornadoes were reported in advance of the storm in northwestern Florida and another at Hilton Head Island near Savannah, Ga., but each caused only minor damage.

Total damage in the States of Louisiana, Florida, Alabama, and Mississippi was $24,774,000 of which $15,204,000 was to crops. Damage in other States such as Georgia, the Carolinas, and Virginia was $100,000 or less and was greatly outweighed by the beneficial rains which relieved drought conditions. Deaths, mainly from plane and automobile accidents attributed to the storm, totalled 15. Warnings throughout the storm were timely and accurate.

The origin of Flossy has been discussed by Hawkins [4] and its transformation to an extratropical storm by Richter and DiLoreto [5].

Hurricane Greta, October 30–November 6.—A depression, which is believed to have had its origin along the intertropical convergence zone over the southern Caribbean, was first noted southeast of Jamaica on October 30 when a Navy reconnaissance flight observed 35-m. p. h. southeasterly winds. Numerous showers and a large area of relative calm near the location of lowest pressure were also observed.

The Woods Hole Oceanographic Institution research vessel *Crawford*, on a weather mission in the Caribbean, was very near the circulation center during the afternoon and evening of the 30th and encountered 25 m. p. h. southeasterly winds and a minimum pressure near 1005 mb. (29.68 in.). A radiosonde observation taken by the *Crawford* shortly after their winds shifted from the southeast to northwest indicated the Low was definitely cold-core as opposed to the warm core associated with hurricanes.

The Low continued northward at about 15 m. p. h. with a gradual intensification and by November 1 the lowest pressure had decreased to 998 mb. (29.47 in.). Winds of 30 to 40 m. p. h. were reported over a large area surrounding the center, but gentle variable winds and calms still covered an extensive area near the center.

A large high pressure system, which had stagnated some distance off the middle Atlantic coast during the last few days of October, blocked further northward movement so that during the night of November 1, the storm looped and took a southeastward course with a somewhat slower speed. It was during this period, as shown by data received from planes of the National Hurricane Research Project, that Greta assumed tropical storm characteristics with a minimum pressure of 992 mb. (29.29 in.).

It is believed that Greta reached hurricane intensity on the afternoon of November 3 or early on the 4th, and continued to intensify until November 5 when winds in excess of 100 m. p. h. and a minimum pressure of 970 mb. (28.64 in.) were reported by reconnaissance aircraft. During this period the forward motion became east-northeast at 20–25 m. p. h. On November 6 and 7 the storm continued east-northeastward at an accelerated speed, gradually assuming extratropical characteristics due to much colder ocean temperatures and an influx of cold air.

In many ways Greta was a most unusual tropical cyclone. For a long period it had all the characteristics of a cold Low from middle latitudes. There is some evidence that it may have been similar to the Kona storms of the Pacific both in origin and size. The rapid intensification to hurricane force with a southeastward movement has been rarely observed. Middle-latitude conditions at this time indicate an energy transfer from upstream may have occurred.

The circulation formed by the hurricane and the large anticyclone to the north covered a tremendous expanse of the Atlantic Ocean and the long fetch of the strong winds set up much larger waves and swells than indicated by the normal wind-sea-swell relationships. On the south Atlantic coast, damage was worst along the Jacksonville beaches where the water is relatively deep a short distance offshore. Damage in Puerto Rico from swells at least 20 feet high was heavy. Sta. Lucia, B. W. I., reported 20-foot swells from the west-northwest and some as much as

25 feet high. The French West Indies suffered severely with 80 percent of the port installations destroyed at Basse Terre, Guadeloupe. Damage, almost entirely from sea action, was as follows:

Jacksonville beaches, Florida	$1, 170, 605
Elsewhere along southeastern U. S. coast	510, 000
Puerto Rico	1, 194, 701
Virgin Islands	45, 000
Dominica	291, 500
Sta. Lucia and Pigeon Island	68, 000
French West Indies	200, 000
Other Caribbean Islands	100, 000
Total	$3, 579, 806

There was one death in Puerto Rico by drowning of the occupant of an exposed house who did not heed a warning to evacuate.

3. OTHER TROPICAL OR QUASI-TROPICAL DISTURBANCES

An unusual number of tropical disturbances which failed to acquire winds of as strong as 40 m. p. h. were noted this year. If entirely tropical in nature, most of them can be classified as tropical depressions which may be defined as weak cyclonic disturbances of tropical origin and with winds less than 40 m. p. h. Since some of these tropical and quasi-tropical disturbances were of some importance, a partial list follows:

Tropical depression, June 17–18.—A tropical depression, which briefly caused squalls up to 40 m. p. h., was located 500 miles east of the south Florida coast on June 17–18. Little evidence of it could be found after 1330 EST on the 18th. The lack of deep easterlies north of the area, and troughy conditions over the disturbance at 200 mb. were considered unfavorable for development.

Tropical depression, July 4–8.—A complete although very weak circulation was noted at 1930 EST on July 4, at Lat. 26.2° N., Long. 86.2° W., developing under a cold trough in the mid-troposphere. It moved north-northwestward and northwestward on the 6th causing gusts of 38 knots at Panama City and moved inland near Pensacola late on the 6th where the lowest barometer noted was 1011 mb. Whatley, Ala., reported 14.22 inches of rain during the storm and 10.85 inches in 24 hours.

Property damage was estimated at $400,000 from the heavy rains, plus $100,000 crop and $3,000 livestock damage. Many highway and railroad bridges were washed out and erosion of roads was extensive.

Tropical depression, August 28–September 6.—On August 28 an unusually strong wave on the intertropical convergence zone began approaching the Cape Verde Islands and soon developed considerable intensity. Station SAL in the Cape Verdes on the 31st observed a barometer reading of 1004 mb. Several ships in the area reported winds of 35 to 40 knots. After leaving the Cape Verde area, the storm apparently gradually decreased in intensity and finally dissipated northeast of the Leeward Islands on the 6th.

Tropical depression, September 13.—A vigorous depression passed through the Cape Verdes on the 13th, attended by squalls. Maximum winds are unknown. The depression was completely damped out before reaching the Antilles .

Tropical depression, October 9.—Some 1,300 miles east of Puerto Rico on this date, ships reported squalls of 40 to 45 m. p. h. and there was evidence of at least a quasi-circulation It was completely damped out within 24 hours.

Tropical depression, October 10–12.—Probably developing from the same easterly wave but farther to the north, a tropical depression formed on October 10 and moved in a general northerly direction for several days without further development. It was not the same depression noted on the 9th.

Quasi-tropical Low, October 13–19.—This Low formed as a wave on a dissipating polar front north of Hispaniola on the 12th and moved west-northwestward to the extreme southeastern Florida coast south of Miami on the 15th, when it turned north and north-northeastward passing over the North Carolina Capes west of Cape Hatteras. Rainfall was excessive in portions of Florida ranging from 6 to 20 inches over a 50-mile wide belt from the northeastern corner of Lake Okeechobee to Jacksonville. This storm never became wholly tropical, and maximum winds and most of the precipitation occurred well in advance of the low pressure center. Highest winds reported were gusts of 60 to 65 m. p. h. and probably some sustained winds of near 60 m. p. h. at sea. Damage from flooding in Florida, particularly around Kissimmee, totaled about $3,000,000. Two persons were drowned in the surf during the storm.

4. POSSIBLE CAUSES OF THE COMPARATIVELY MILD HURRICANE SEASON

One of the currently accepted requirements for hurricane formation is a warm sea surface with temperature 80° F. or higher. Riehl [6], however, has failed to find useful correlations between sea surface temperature anomalies and hurricane formation on a monthly or yearly basis. At the same time when the time scale of correlation was increased to 5 years and more, some improvement in the correlations was noted.

On the other hand, Fisher [7] has found some evidence, although not conclusive, that hurricanes tend to form near relatively warm ocean areas, that they tend to follow tracks along the areas of warmest water, and that they tend to weaken when they move over pronouncedly colder water. Some of the examples cited by Fisher appear to require a high degree of subjective interpretation.

At the time of preparation of this article, the sea surface temperature anomalies for this hurricane season have been analyzed for June, July, and August. During these months, sea surface temperatures appear to have been near or above normal everywhere in the western and central portions of the tropical Atlantic. Samplings for October indicate negative departures from normal [8]. Since sea

surface temperature anomalies are probably a result of abnormalities in the general circulation, it may be difficult to separate the effect of each in inhibiting or encouraging hurricane incidence.

Another generally accepted requirement for hurricane development is the existence of some preexisting disturbance. Easterly waves reaching the eastern Antilles appear to have been about normal in number but perhaps weaker than usual. The number of tropical depressions which failed to develop into tropical storms was greater than normal and this was particularly true in the western tropical Atlantic throughout the season and in the Cape Verde region in August and September.

Thus, largely by the process of elimination we are forced to turn to the general circulation in an effort to find the causes of the subnormal hurricane season. The requirements of an essentially barotropic atmosphere in the low and middle troposphere and a deep easterly current are provided by certain circulation types. In June the subtropical ridge was located considerably north of its normal position in the eastern United States and most of the Atlantic. Namias and Dunn [1] have indicated that this is favorable for tropical storm activity. To a lesser extent this same situation obtained in October and in both these months tropical storm activity was normal or above.

However, from early July into early September, the circulation over the Atlantic Ocean in 1956 differed radically from that of 1954 and 1955 and indeed many of the years since the early 1930's. In 1954 and 1955 the westerlies were far north of their normal position and during the greater part of 1956 were south of their average position. According to Jerome Namias,* fast westerlies (the speed of the westerlies is usually above normal when their principal axis is comparatively far south) inhibit the deployment into the Tropics of deep polar air masses which must be prolonged and persistent to provide a favorable upper-air climate for hurricane genesis. Unusually low-latitude westerlies in the Atlantic contract the area of deep easterlies. This same circulation type tends to shunt any hurricanes which do form away from the North Atlantic and Middle Atlantic coasts. At the same time, even though the overall hurricane frequency decreases, hurricane activity increases somewhat locally over the Gulf of Mexico, Florida, and the Caribbean.

During most of September, the position of the strongest westerlies was about normal and there were a considerable number of incipient tropical disturbances (depressions) which failed to intensify materially. In other words, there was some persistent inhibiting factor which has not yet been identified. It may have been subnormal sea temperatures in some areas, unfavorable upper-troposphere conditions, or some facet of the general circulation. Although Hawkins [4] found that circulation over the Atlantic in September resembled that of 1955 to a considerable extent and that strong and deep subtropical easterlies were prevalent, this never seemed to be the case in the area where the depressions formed. Almost invariably these disturbances formed under a relatively cold trough which we normally consider an unfavorable location for hurricane development.

Hawkins [8] has pointed out that the mean circulation pattern at 700 mb. during October 1956 was similar to patterns that Ballenzweig [9] found to be generally favorable to hurricane development and subsequent incidence in the Florida area. To account for the single quasi-tropical Low this October, Hawkins noted that a sampling of sea surface temperatures over the Gulf, Caribbean, and tropical Atlantic indicated below normal values for the month, but he made no attempt to relate this anomaly to the atmospheric circulation of preceding months.

*Personal communication to the authors.

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THE WEATHER AND CIRCULATION OF DECEMBER 1956[1]

A MONTH WITH LARGE WEEKLY FLUCTUATIONS

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1. ZONAL INDEX AND GENERAL CIRCULATION

December's mean circulation in the Northern Hemisphere was quite asymmetrical about the North Pole, as shown by the fields of mean 700-mb. height and its departure from normal (fig. 1). The large positive anomaly over northern Siberia, for instance, contrasted with negative values at similar latitudes in the Western Hemisphere. It is not unusual for adjacent regional circulations to be different in form, in the sense that one may exhibit high-index characteristics while low index is observed in the other [1, 2, 3]. Such was the case in December 1956. It is perhaps more unusual for the entire Western Hemisphere to fit into the high-index category as well as it did this month.

While no quantitative measure of circulation indices is routinely available for the Eastern Hemisphere, the departure from normal (DN) pattern in figure 1 leaves little doubt that a low zonal index and high-latitude blocking were dominant features of the circulation in that region. The positive anomaly center (+550 ft.) over northern Siberia was the largest 700-mb. height departure from normal in the Northern Hemisphere. An extension of the surrounding positive DN field eastward to the Bering Sea was accompanied by a large area of negative anomaly in the west-central Pacific.

Eastward from the central Pacific, however, the pattern exhibited a number of features typically associated with high index, among them an unusually deep Icelandic Low and abnormally strong subtropical ridges in the eastern Pacific and western Atlantic Oceans. Some westerly component of mean 700-mb. DN flow was observed over the entire extensive area bounded by 40° and 60° N. lat., and 140° W. long. eastward to central Europe.

An index cycle of some 5 weeks' duration was terminated with December's high values shown in figure 2. The cycle was remarkable because of its amplitude, with a range of more than 9 meters per second in 5-day mean values, from a low of 6.5 m. p. s. in late November to a high of 16 m. p. s. in December. Namias [1] indicated that November might be a favorable time for index cycles, although the principal cycle usually occurs in February or March. The marked variations of the Western Hemisphere zonal index this month will be discussed in subsequent paragraphs on intramonthly variability.

[1] See Charts I–XVII following p. 458 for analyzed climatological data for the month.

TABLE 1.—*Stations reporting highest average December temperature (°F.) of past 50 years in December 1956. All are new records except those marked* *

Station	Mean temperature	Positive departure from normal
Macon, Ga.	56.3	6.6
Baltimore, Md.	46.5	7.7
Atlantic City, N. J.	45.2	7.0
Asheville, N. C.	49.3	9.1
Charlotte, N. C.	53.1	10.1
Winston-Salem, N. C.	49.8	9.2
Columbia, S. C.	56.2*	9.2
Florence, S. C.	56.3	9.8
Chattanooga, Tenn.	51.4	9.3
Knoxville, Tenn.	51.4*	10.4
Nashville, Tenn.	50.3*	8.7
Lynchburg, Va.	47.7*	8.8
Norfolk, Va.	52.2	9.4
Richmond, Va.	48.9	9.4
Charleston, W. Va.	46.9	8.8
Elkins, W. Va.	42.1	9.2

*Higher temperatures were observed in December 1889.

The geographical distribution of wind speeds at 700 mb. accompanying Siberian blocking and downstream high-index is well illustrated in figure 3. In the Pacific the mean 700-mb. jet stream was depressed southward from both the November 1956 (dashed) and the December normal (not shown) positions. Downstream however, the westerlies were close to their normal December location, but unusually strong, as shown by wind speeds in excess of normal (fig. 3B) along the entire route of the mean 700-mb. jet stream.

2. ZONAL INDEX AND UNITED STATES WEATHER

United States temperatures reacted to the increased zonal index in striking fashion by warming extensively (with respect to normal) over the preceding month. Of 100 representative stations, 79 were warmer than in November by one or more temperature anomaly classes (out of 5) and only 6 were colder by at least one class. One or more stations in 8 States reported record high average temperatures for December (see table 1), while new record daily highs were established in 27 States.

Much above normal temperatures in the East (see Chart I-B) were closely related to the unusual strength of the Bermuda High. Figure 1 shows positive values of 700-mb. height anomaly over this area, together with a

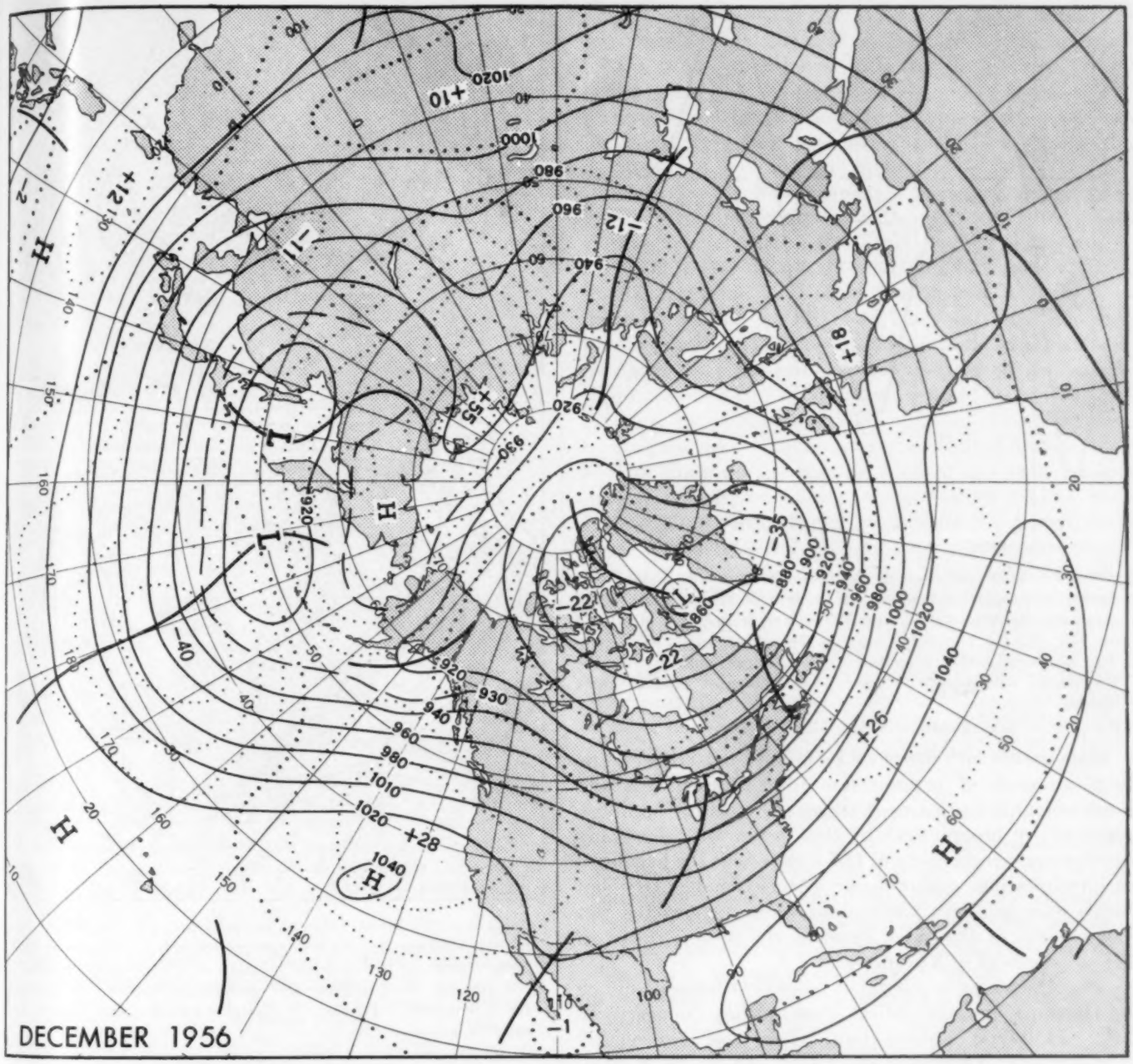


FIGURE 1.—Mean 700-mb. contours and height departures from normal (both in tens of feet) for December 1956. The contrast between Eastern and Western Hemisphere circulation characteristics is readily apparent in the departure from normal pattern.

southerly component of 700-mb. DN flow. Less directly related was the northward displacement (from normal) of preferred paths of daily systems (Charts IX and X). The principal anticyclone path in figure 4B, for instance, illustrates the tendency for cold polar continental Highs to "glance" eastward this month, instead of penetrating the subtropical ridge in the Southeast. According to Klein [4], an anticyclone track of this sort, passing just north of the Great Lakes, is quite common in winter when the westerlies are strong.

The weather in the eastern half of the United States was not predominantly dry as customary with high zonal index values, probably because of the abundant moisture supplied by southerly DN flow from the Gulf. Figure 4A, showing the paths of maximum cyclone frequency, helps explain the rather complicated distribution of precipitation in the eastern United States, where three separate bands of above normal amounts were located (Chart III-B). Heavy precipitation near the north central border and from Missouri to New England was attributable to cyclone activity. The southernmost zone, from eastern Texas to the southern Appalachians, probably resulted from lifting, partly orographic and partly frontal in nature.

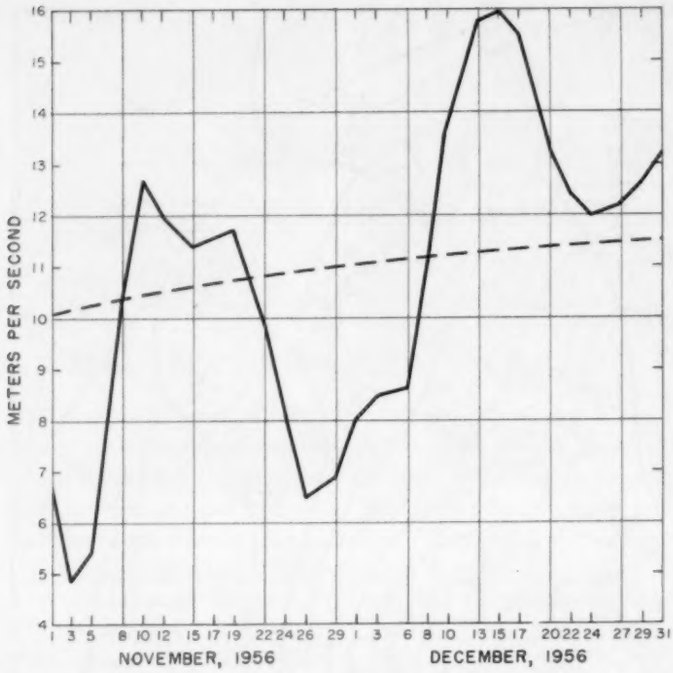


FIGURE 2.—Time variation of the temperate-latitude zonal index (average strength in meters per second of the 700-mb. zonal westerlies between 35° N. and 55° N. and from 5° W. westward to 175° E.) for November through December 1956. The solid line connects 5-day mean zonal index values (plotted at the middle of the period). Dashed line indicates normal index values.

More in line with the usual high-index pattern were the large amounts of precipitation in the Northwest and lesser amounts downstream, where the moisture had been removed by orography. In the Southwest, where any northeasterly component of DN flow lessens the likelihood of precipitation, amounts were very small. Dry hot winds over southern California's forest regions the last three weeks of December renewed the serious threat of fire so prevalent in November.

After the temporary drought relief in October described by Hawkins [5] many critical areas finished the year with little additional precipitation. This was particularly true of western Oklahoma and Texas, and central Kansas. The year ended as a record dry one over portions of Iowa, Kansas, Oklahoma, Texas, New Mexico, Arizona, and Florida. The greatest deficits in Florida occurred in coastal areas of the southern half of the State.

3. INTRAMONTHLY VARIABILITY

Dunn, in the previous article of this series [6], described the pronounced intramonthly fluctuation of circulation and weather patterns in November and pointed out indications of some stability of circulation in the last two weeks. The persistence was short-lived, however, and subsequent changes seemed large enough to justify continuation into December of the analysis by weekly periods. Five-day mean 700-mb. charts in figure 5 and wind profiles

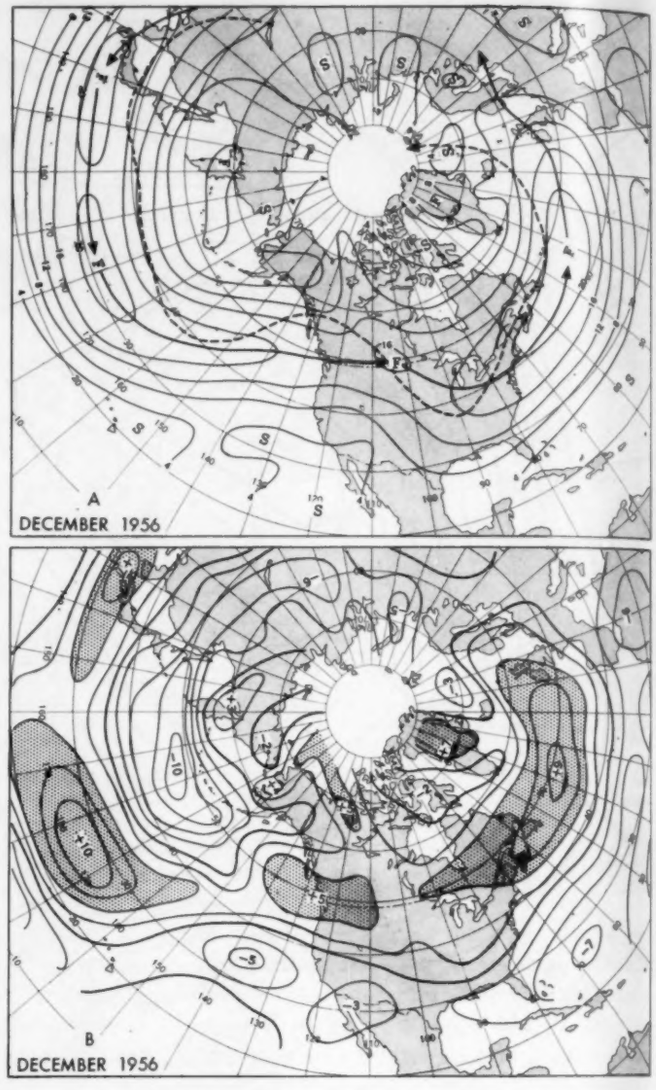


FIGURE 3.—(A) Mean 700-mb. isotachs and (B) departure from normal wind speed (both in meters per second) for December 1956. Solid arrows in (A) indicate position of the primary jet axis at the 700-mb. level in December and dashed arrows the position for November. "F" and "S" designate wind speed maxima and minima.

in figure 6 were selected to represent circulations associated with the 7-day periods of temperature anomaly shown in figure 7 and the precipitation totals in figure 8.

Some idea of the magnitude of Western Hemisphere circulation changes during the month is shown in figure 2, where 5-day mean values of the zonal index are represented by the solid curve. The similarity between the index behavior in November and December is shown by this curve, in that the highest values occurred toward the middle of each month with much lower values at either end. The overall average was much higher, however, in December than in November. Another feature common to both months was a reversal in United States circulation. Both months began with a mean trough in the West and a mean ridge in the East, and ended with

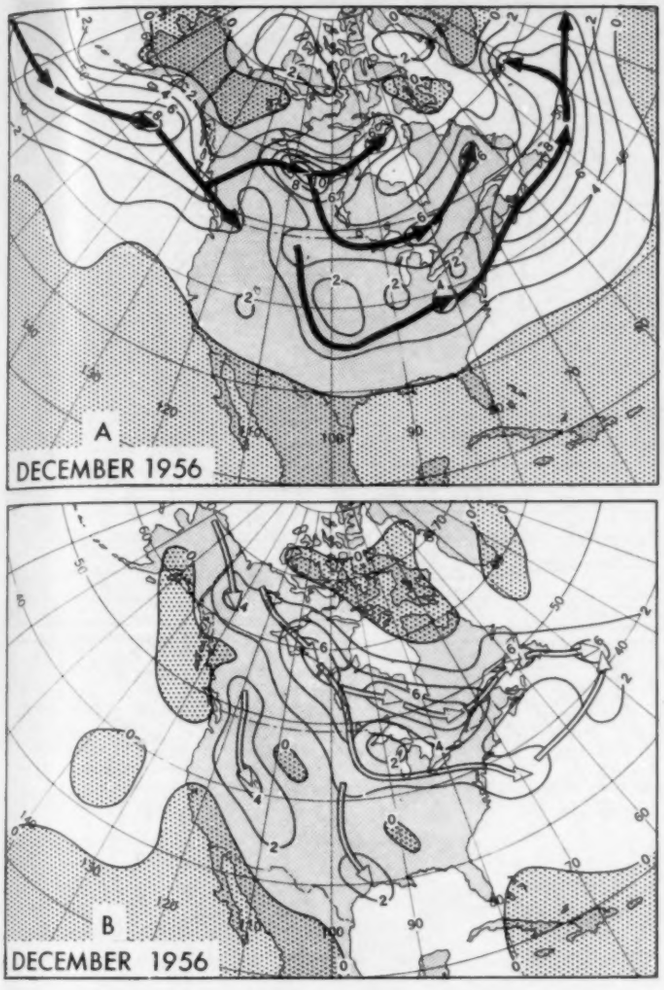


FIGURE 4.—Frequency of cyclone passages (A) and anticyclone passages (B) (within 5° squares at 45° N.) during December 1956. Well-defined cyclone tracks are indicated by solid arrows and anticyclone tracks by open arrows.

the opposite pattern. The 700-mb. maps of the final week in each month were remarkably alike.

DECEMBER 3–9

The 5-day mean 700-mb. height and departure from normal chart for December 4–8 (fig. 5A) displays a strong blocking anticyclone over the Bering Sea. This center is believed to have been largely the result of discontinuous retrogression, in a week's time, of a mean ridge from western North America. To its south a mean trough, associated with negative 700-mb. height anomalies of more than 600 feet, remained nearly stationary.

During the same week the 5-day mean ridge over the western United States was replaced by a mean trough. A similar reversal took place in the eastern United States, where a 380-foot negative DN center was replaced by the 370-foot positive center shown in figure 5A. In the Atlantic the pattern flattened considerably and the westerlies increased at mid-latitudes, as the zonal index continued to rise from the strongly below normal values of late November (fig. 2). The 5-day mean wind speed profile in figure 6A clearly outlines the latitudinal extent of the wind speed deficit with respect to normal during this week.

Over the United States there appeared an apparent deviation from the usual relationship between surface temperature anomaly and 700-mb. DN flow [7]. While the DN flow reversed completely from north-northeasterly to south-southwesterly over the central United States, surface temperatures fell sharply (fig. 7a). This was due to the intrusion of an extremely cold but shallow mass of Arctic air into the United States from Canada. The propelling force for this cold air outbreak is shown by strong northerly DN flow over Alaska and western Canada in figure 5A. Since the shallow cake of air was shielded from opposing upper-level flow by the Rocky Mountain barrier, its momentum was sufficient to allow strong southward penetration into central United States.

The front at the leading edge of the cold air mass became nearly stationary in the eastern United States and the Southern Plains in a zone delineated rather well by the southern boundary of heavier precipitation observed for the week (fig. 8a). The adjoining article by Smith and Wilhelm [8] describes the precipitation associated with this cold front, as warm Gulf air overran the cold polar air. Lesser amounts accompanied the cold front as it moved slowly, but with limited moisture, over and west of the Continental Divide. The mean trough and orographic features along the West Coast contributed to significant precipitation totals from central California northward.

DECEMBER 10–16

Much of the positive anomaly center associated with the Bering Sea blocking anticyclone of early December had retrograded to northern Siberia by mid-month. During the same period a mean trough near the eastern Asiatic coast weakened at all but low latitudes. Thus the Pacific was left with but one mid-latitude mean trough, represented in the DN pattern by a large area of below normal anomaly in the west central Pacific (fig. 5B). This latter mean trough had retrograded to a position favoring the wavelength adjustment which was partly responsible for rising zonal index downstream.

The 5-day mean zonal index for the Western Hemisphere this week reached 16 meters per second, the highest observed for any 5-day mean period of the 14 Decembers of record. Factors associated with this high index value included strong development of the eastern Pacific and Bermuda Highs [1, 9] and a vigorously deepened Icelandic Low.

Figure 2 illustrates the rapidity of the index changes, and figure 6, the latitude band most affected by the changes. For instance, in figure 6B the 5-day mean wind speed between 45° N. and 50° N. increased over 10 m. p. s. from the December 4–8 value.

Rising heights and increasing westerlies at the 700-mb.

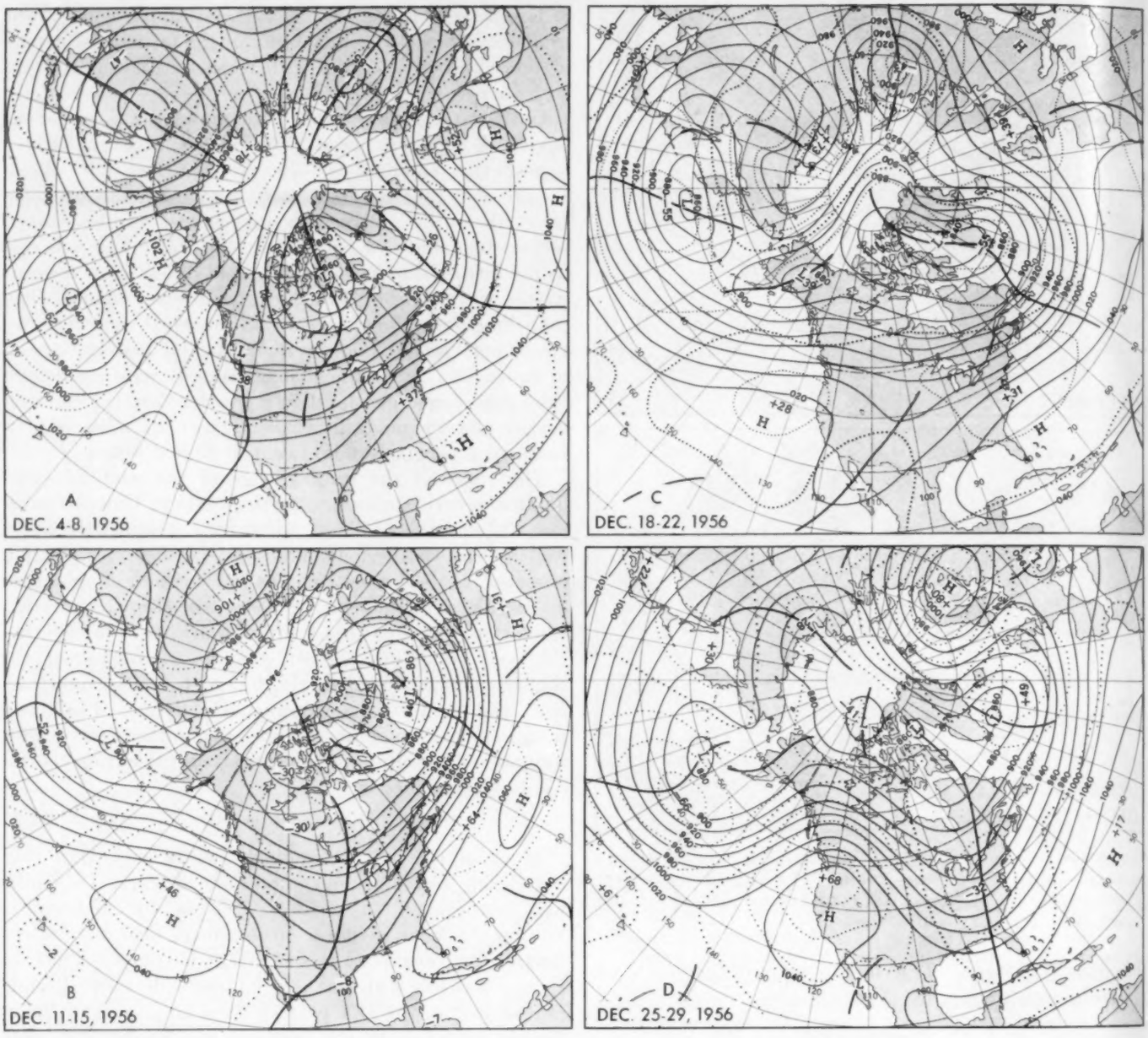


FIGURE 5.—Five-day mean 700-mb. contours and height departures from normal (both in tens of feet) for selected periods in December 1956 one week apart. Lack of persistence from week to week was an outstanding aspect of circulation in December.

level over western United States caused rapid warming over this area, except in Arizona and New Mexico where northerly DN flow prevailed. Foehn warming just east of the Continental Divide was extensive from Montana to the Texas Panhandle, but some cooling accompanied a new wedge of Canadian air in a broad zone roughly 700 miles wide from eastern Texas to southern Lake Michigan (see fig. 7b). While this outbreak of Continental Polar air was weaker than its predecessor, associated frontal precipitation amounts were enhanced by an approaching mean trough (fig. 5B), and large totals were accumulated from Louisiana to the southern Appalachians. Damaging storms of freezing rain and snow in the Northeast, and heavy frontal and orographic rains in the Northwest highlighted the week's precipitation pattern.

DECEMBER 17–23

Changes this week were much less pronounced in the Western Hemisphere than in the previous week, with small displacement and weakening centers of action the general rule. Notable exceptions were cyclonic development in the Gulf of Alaska and rising heights in the North European-Icelandic area (fig. 5C). Zonal westerlies (figs. 2 and 6) diminished as the Icelandic Low filled and the western Atlantic mean ridge weakened and retrograded. Positive values of 700-mb. height anomaly

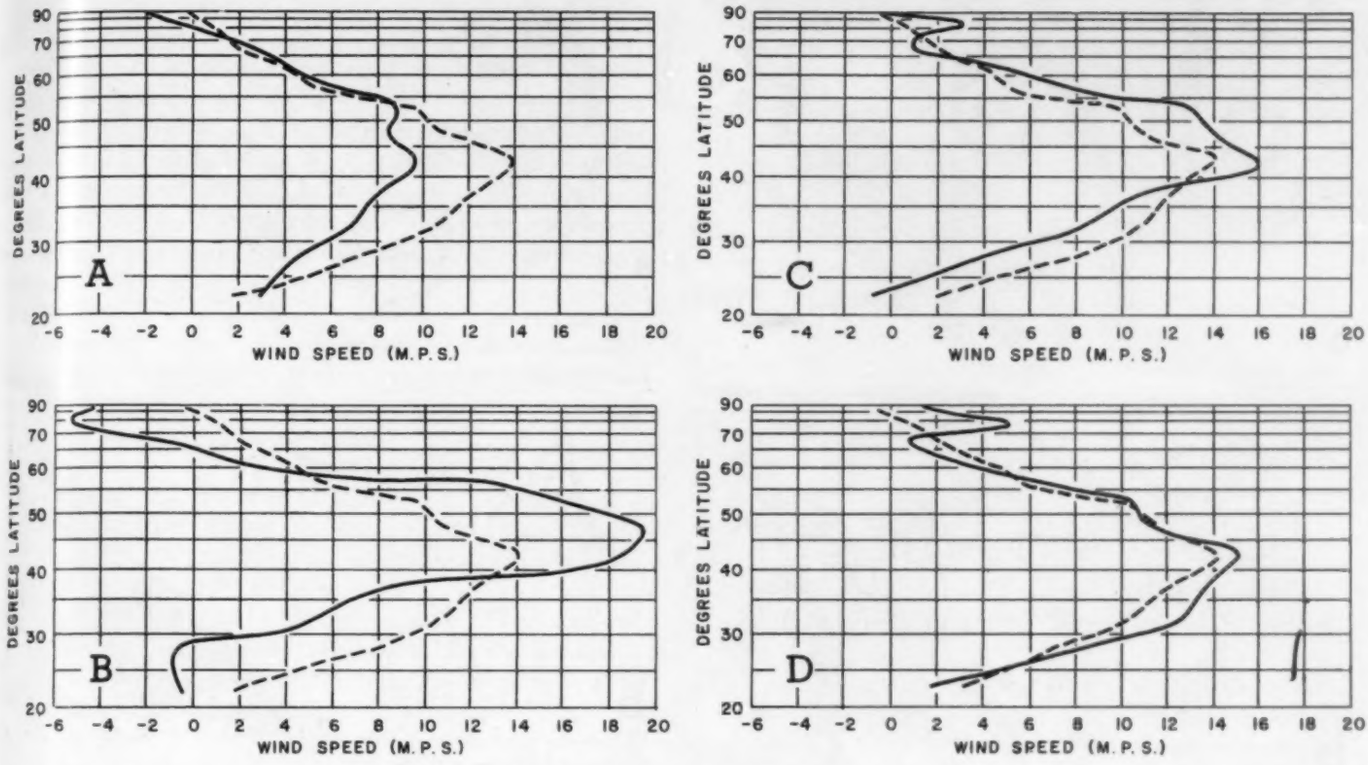


FIGURE 6.—Five-day mean zonal wind speed profiles in the Western Hemisphere (0° westward to 180°) for following periods (corresponding to those in fig. 5): (A) Dec. 4–8, (B) Dec. 11–15, (C) Dec. 18–22, (D) Dec. 25–29, 1956. Note sharp increase in westerlies at mid-latitudes from A to B and decline from B to C.

bridged the United States mean trough in the North, leaving the most active portion in the Southwest.

These circulation changes encouraged further warming across the northern third of the United States (fig. 7c), except for New England where progressively weaker bursts of cold air still had a cooling effect. The Southeast remained much above normal for the third consecutive week, and the Southwest remained cool under the influence of northeasterly DN flow in the mean trough.

Precipitation was moderate to heavy in a broad band from central Texas to northern Florida, extending northeastward to southern Michigan and southern New England. Over-running moist Gulf air was also responsible for widespread fog over the eastern half of the United States, thus hampering air transportation during the pre-Christmas weekend.

DECEMBER 24–30

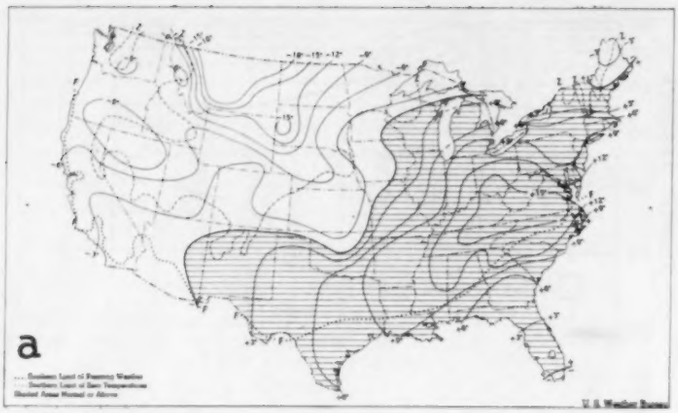
Extreme changes from the previous week over virtually the entire Northern Hemisphere can be seen by comparing the patterns of figure 5D and 5C. Rises at 700 mb. of 600 to 800 feet over Scandinavia contributed to almost complete breakdown of the Siberain blocking High, remnants of which were joined with the subtropical ridge off the east coast of Asia. Farther downstream, the Pacific mean trough remained strong and progressed to the central Pacific, while the eastern Pacific mean ridge built strongly and pushed into western North America. The mean trough in southwestern United States grew in amplitude and intensity as it progressed to eastern United States. It is surprising to note that these pronounced changes in longitudinal position and amplitude of wave train components from the central Pacific to the western Atlantic produced relatively minor changes in the wind speed profile (fig. 6D), and the zonal westerly index (fig. 2).

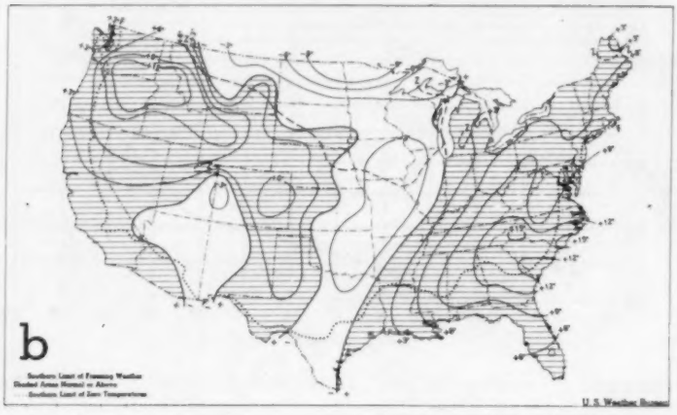
Oscillation of the United States 700-mb. mean pattern from that observed early in the month (fig. 5A) had, by the final week of December, produced a picture very similar to that of November's final week (fig. 6 of [6]). The oscillation was strongly reflected in the temperature pattern, especially in the Southeast where temperature anomalies decreased by 12 to 15° F. A well developed Great Basin High expanded the area influenced by radiational cooling, and warming (with respect to normal) occurred over the Great Plains.

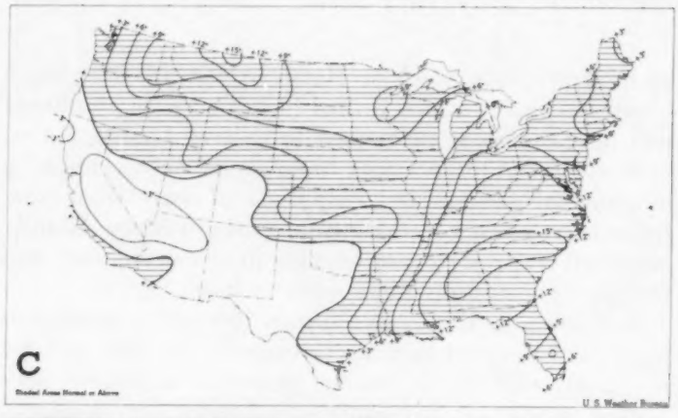
Some modification of the precipitation picture accompanied the strong ridge buildup in the West and eastward progression of the mean trough. Both changes tended to dry out the country, the former by increasing stability and the latter by cutting off the Gulf moisture source.

4. SUMMARY

The general circulation of December 1956 was mainly comprised of two separate, interdependent, regional pat-







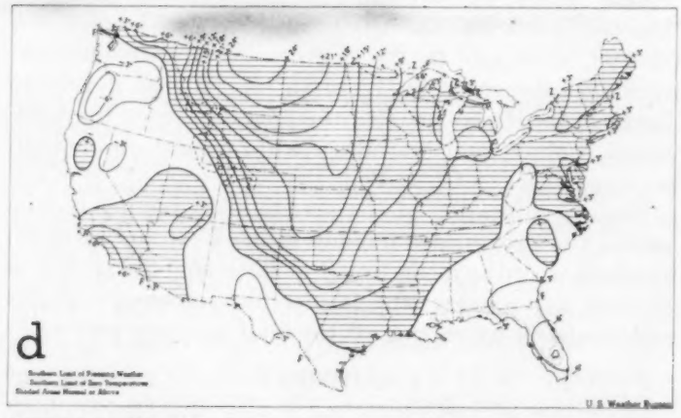
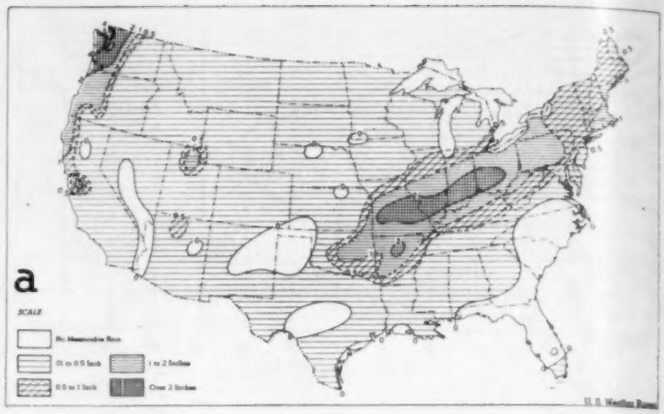
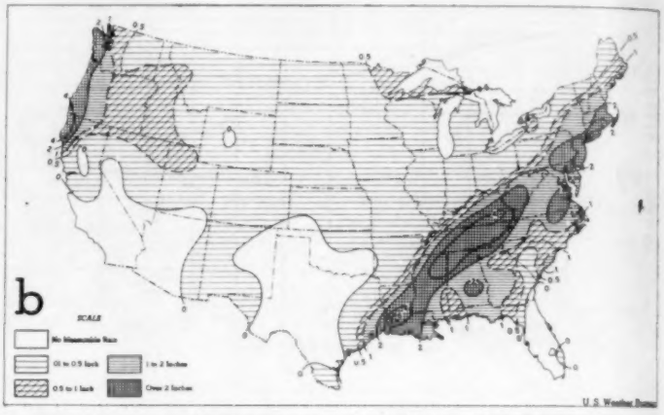
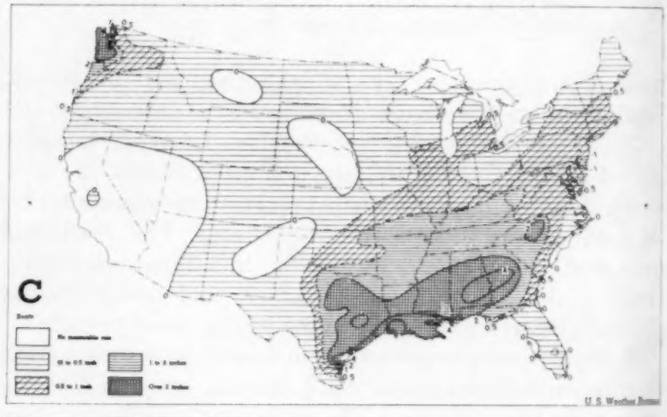


FIGURE 7.—Departure of average surface temperature from normal (° F.), centered on weekly periods corresponding to those of figure 4, (a) Dec. 3–9, (b) Dec. 6–10, (c) Dec. 17–23, and (d) Dec. 24–30. (From *Weekly Weather and Crop Bulletin, National Summary*, vol. XLIII, Nos. 50–53, Dec. 10, 17, 23, 31, 1956).







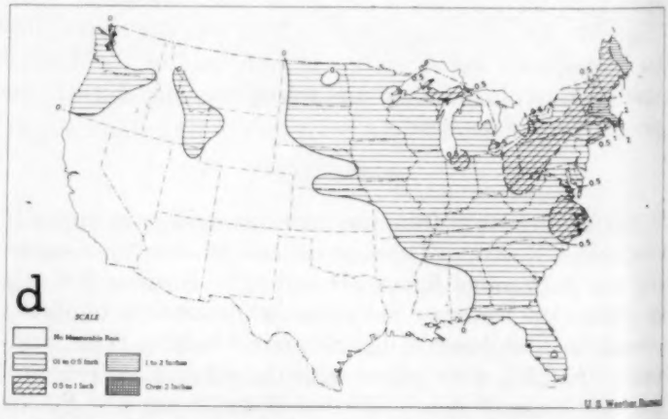


FIGURE 8.—Total precipitation (inches). (a) Dec. 3–9, (b) Dec. 6–10, (c) Dec. 17–23, and (d) Dec. 24–30, 1956. (From same source as figure 7.)

terns. Low-index and blocking characterized the Eastern Hemisphere circulation, while in the Western Hemisphere the 5-day mean zonal index reached its highest December value in 14 years of record.

United States temperature anomalies reflected the high-index character of the Western Hemisphere circulation by warming at least one class from the previous month at 79 of 100 representative stations to break records for the month in 8 States and daily records in 27 States.

Intramonthly variability was a conspicuous circulation feature, as evidenced by fluctuations of the zonal index and a complete oscillation of the mean trough-ridge structure over the United States.

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Water Supply Forecast for the Western United States

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PRECIPITATION ASSOCIATED WITH A COLD FRONT, DECEMBER 7–9, 1956

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1. SYNOPTIC EVENTS

During the period December 7–9, 1956, a slow-moving cold front over the Central States brought prolonged precipitation to an area extending from northern Texas northeastward into New England (fig. 1). Amounts of over 3 inches accumulated in portions of southern Illinois and Indiana. Accumulations of 1 inch or more were reported from northeastern Oklahoma to Lake Erie.

Prior to this period, a cold front had moved through the Northern Plains States at about 15 miles per hour until 0630 GMT, December 6. It then became nearly stationary from Oklahoma to Illinois, although the portion north of Illinois continued an eastward movement. By 0630 GMT, December 7, the front extended along a line from southern Oklahoma through the eastern Great Lakes to a Low center in the St. Lawrence River Valley (fig. 2). A High pressure system moved southward behind the front and covered most of the Northern Plains States by 0630 GMT, December 7.

The upper air flow at 0300 GMT, December 7 (fig. 3), was marked by a broad belt of southwesterly winds at 500-mb. over all the United States except the Pacific Coast States. A trough lay from northern Idaho south-southwestward through central California and a large-amplitude ridge west of it extended northward into the Gulf of Alaska. The flow aloft east of the trough was remarkably free of curvature, and remained almost straight west-southwesterly over the Central States during the entire period of rainfall.

Several very minor waves formed along the front, but none developed significantly.

The surface High over the Northern Plains States had continued to intensify and, moving southward, had merged with an even stronger High pressure cell, also moving southward, which had formed in British Columbia. By 0630 GMT, December 9 (fig. 4) there was a 1055-mb. High near Salt Lake City, Utah, with a strong ridge extending southeastward.

During the 72 hours from 0630 GMT, December 6 to 0630 GMT, December 9, the portion of the front from Texas to the Great Lakes area moved only about 200 miles southeastward. One section, from western Tennessee to West Virginia, was almost stationary during the last 24 hours of that period. The southwestern section, however, maintained a slow southeastward drift until 1830 GMT, December 8, when it lay along a line from Nashville, Tenn. to Shreveport, La. and Del Rio, Tex. During the next 12 hours the portion of the front southwest of Nashville accelerated. By 0630 GMT on the 9th it lay across Mississippi and well east of Brownsville, Tex. This rapid frontal movement, accompanied by strong anticyclogenesis over the northern and western portions of the country, contributed significantly to the development of a surface Low in the East, which subsequently brought an end to the rainfall in the area of this study.

The 500-mb. chart had remained essentially unchanged from December 6 through December 8, with the long-wave trough in the West moving only as far as eastern Montana-Salt Lake City-Yuma by 0300 GMT on the 8th. However,

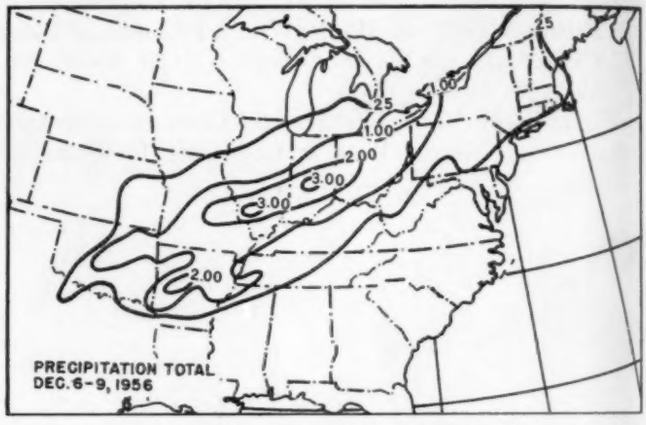

FIGURE 1.—Approximate total precipitation for the period 1230 GMT, December 6 through 1230 GMT, December 9, 1956. Units are inches.

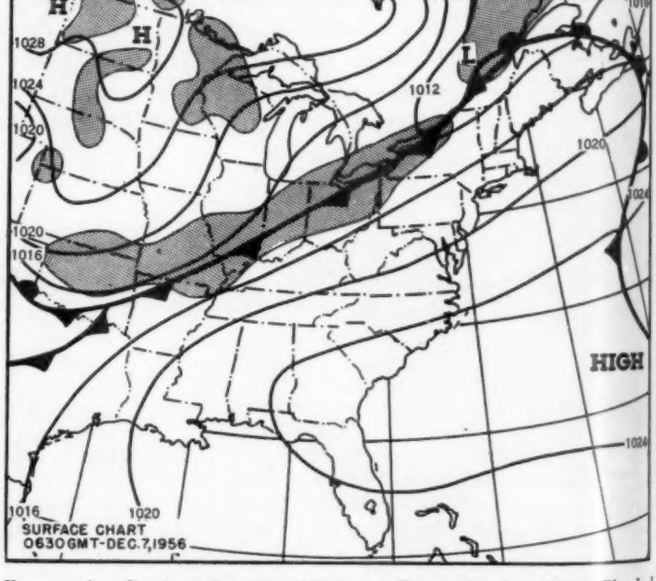

FIGURE 2.—Surface chart for 0630 GMT, December 7, 1956. Shaded areas indicate current precipitation.

by 0300 GMT, December 9 (fig. 5), the trough had accelerated eastward with a marked increase in wind speeds at 500 mb. over the Central States and the eastern Great Lakes-Ohio River Valley areas. This gave impetus to the surface Low forming in the East and by 0630 GMT, December 10, had effectively halted all precipitation in the eastern half of the country.

2. PHYSICAL PROCESSES RELATED TO LOW-LEVEL CONVERGENCE

In any prolonged precipitation situation such as the one being considered there is doubtless some low-level convergence occurring. Petterssen [1] has derived an equation which shows the factors related to the production of low-level convergence. This investigation sought to study the terms of that equation as applied to this case. Means [2] has investigated a case of flood-producing rains in the Chicago area in this manner.

The development equation of Petterssen is:

$$-\eta_0 D_0 = A_\eta + \mathbf{V}_0 \cdot \nabla \eta_0 - \frac{g}{f}\nabla^2 A_h - \frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\overline{\omega(\Gamma_a-\Gamma)}\right] - \frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\frac{1}{c_p}\overline{\frac{dW}{dt}}\right]$$

where subscript 0 designates a value at 1000 mb. and the bar an average value for the layer from 1000 mb. to the level of non-divergence. η is the vertical component of absolute vorticity; D is the divergence of the wind vector $\mathbf{V}$; A_η is the vorticity advection for the level of non-divergence; ∇ is the gradient vector operator in a constant-pressure surface; g is the acceleration of gravity; f is the Coriolis parameter; A_h is the thickness advection for the layer from 1000 mb. to the level of non-divergence; R is the gas constant; p is pressure; $\omega \equiv dp/dt$ is a measure of vertical motion (negative value indicates upward motion); $\Gamma_a \equiv dT/dp$ is the adiabatic lapse rate of temperature T with respect to p; $\Gamma \equiv \partial T/\partial p$ is the actual lapse rate with respect to p; c_p is specific heat at constant pressure; W is the heat (other than latent) supplied to a unit mass of air by non-adiabatic processes.

The terms in the development equation represent the following physical processes:

$-\eta_0 D_0$ is a measure of cyclonic development at 1000 mb.

A_η is vorticity advection at level of non-divergence.

$-\mathbf{V}_0 \cdot \nabla \eta_0$ is vorticity advection at 1000 mb.

$-\frac{g}{f}\nabla^2 A_h$ is the development contribution of thickness advection for the layer 1000 mb. to level of non-divergence; it is proportional to the Laplacian of thermal advection for the layer.

$-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\overline{\omega(\Gamma_a-\Gamma)}\right]$ is a "buoyancy term" and repre-

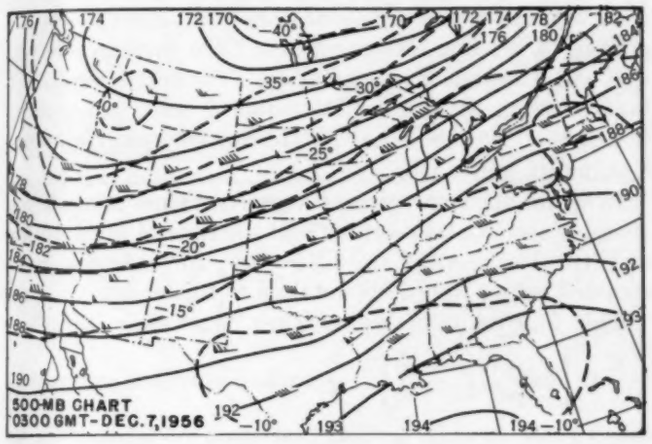

FIGURE 3.—500-mb. chart for 0300 GMT, December 7, 1956. Contours (solid lines) at 200-foot intervals are labeled in hundreds of feet. Isotherms (dashed lines) are at intervals of 5° C. Barbs on wind shafts are for speeds in knots (pennant=50 knots, full barb=10 knots, and half barb=5 knots).

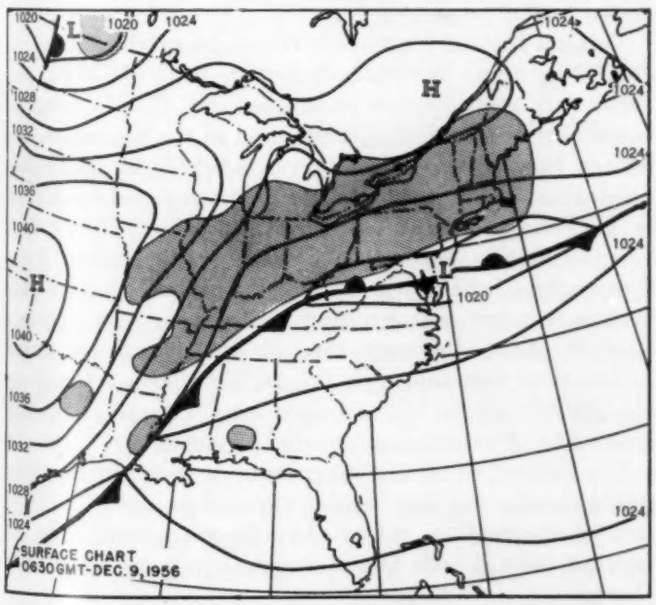

FIGURE 4.—Surface chart for 0630 GMT, December 9, 1956.

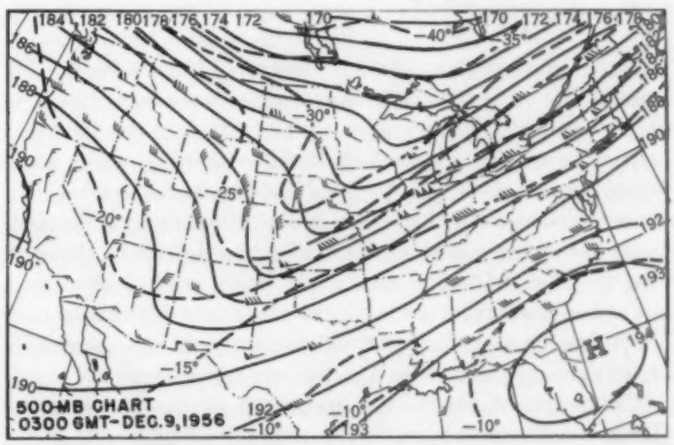

FIGURE 5.—500-mb. chart for 0300 GMT, December 9, 1956.

sents the development contribution of local thickness changes due to adiabatic processes.

$-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\frac{1}{c_p}\frac{\overline{dW}}{dt}\right]$ is the development contribution of local thickness changes due to non-adiabatic processes.

The terms on the right of the equation do not represent independent processes. Actually, the advective processes and the adiabatic and non-adiabatic influences are interacting to produce a very complex atmospheric process. Since the objective of this study is to determine whether or not the terms contributed to low-level convergence, and not to compare their magnitudes, they have been investigated separately. The level of non-divergence was not specifically located in this case, but was assumed to be near 500 mb. If it were as high as 300 mb., it is not likely that a change of sign would result in any of the terms of the equation.

In order to study the vorticity advection at the level of non-divergence (A_g), the vorticity at 500 mb. was computed using the finite difference method and a grid distance of 400 km. The vorticity field was then superimposed on the 500-mb. contours. It was apparent that only slight advection occurred on December 7 and 8, but it was positive in sign as the equation would require. On December 9, when the upper trough approached from the West (fig. 5), the vorticity advection increased but lagged considerably behind the sea level front. An examination of the 300-mb. charts added nothing in this case since the flow was essentially the same as that at 500 mb.

The second term of the equation, the vorticity advection at 1000 mb. ($-\mathbf{V}_o\cdot\nabla\eta_o$), is usually very small, according to computations by Petterssen. Examination of the sea level charts in this case (figs. 2 and 4) shows only slow development of cyclonic vorticity at low levels during most of the period of precipitation. The vorticity development came late in the period with the surface Low forming east of the area of heaviest rainfall. Consequently, this term was considered to be of little importance in the production of convergence.

The third term $\left(\frac{g}{f}\nabla^2 A_h\right)$, a measure of the effect of thermal advection, was studied by means of the 1000–500-mb. thickness charts. The thickness lines were superimposed on the sea level isobars, and the advection of the field was computed as the product of the geostrophic wind component and the thickness gradient measured over a distance of 100 nautical miles. Multiplication by a suitable factor gave the result as thermal advection in ° C. per 12 hours. The field of thermal advection was plotted on a chart and the Laplacian computed by finite differences over a 200-km. grid. Figure 6 contains a few representative charts giving the results of these computations.

The reliability of the computations of the Laplacian of thermal advection is naturally dependent upon the abundance of points at which it is possible to compute the advection. In the method used here points were chosen in all rectangles formed by the intersections of thickness lines and isobars. This resulted in 15 to 25 points being used at each upper air observation time. The areas of negative or positive Laplacian are fairly well defined by this density of points.

Figure 6A shows the area of negative values of the Laplacian of thermal advection extending from Little Rock, Ark., to Indianapolis, Ind., to Syracuse, N. Y. This area, where the thermal advection was contributing to low-level convergence, lies immediately ahead of the cold front. Isochrones of the onset of precipitation (not illustrated) show a steady progression from 1300 GMT, December 6 at Columbia, Mo., through 2100 GMT at Springfield, Ill., to 0100 GMT, December 7 at Indianapolis, Ind., and to 0500 GMT, at Dayton, Ohio.

In figure 6B, the region of negative values of the Laplacian of thermal advection over Ohio corresponds very well with the area of precipitation. The correspondence is best between 0300 GMT, December 7 and mid-morning December 7 at such cities as Toledo, Dayton, Columbus, Cincinnati, and Akron.

In figure 6C, the region of negative values is again just ahead of the frontal position, and the time of precipitation at Little Rock, Ark., and Cairo, Ill., for example, corresponded rather well with the time of this chart.

The fourth term, called the "buoyancy term", is $-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\overline{\omega(\Gamma_a-\Gamma)}\right]$. $\frac{R}{f}$ can be considered constant because there is only a small variation of latitude in the precipitation area. By choosing $p_o=1000$ mb. and $p=500$ mb., $\ln\frac{p_0}{p}$ also becomes a constant. The element to investigate is therefore reduced to the Laplacian of the average product $\overline{\omega(\Gamma_a-\Gamma)}$, which may be approximated by the product $\bar{\omega}\ \overline{(\Gamma_a-\Gamma)}$.

Vertical motion charts are routinely produced by the Joint Numerical Weather Prediction Unit (JNWP), and these were used for this parameter (fig. 7). It must be noted here that in this equation and in the accompanying figures, upward vertical motion is indicated by a negative value of $\bar{\omega}$. Also, vertical motion as computed by JNWP is the motion at the 500-mb. level rather than the average vertical motion from the surface to the level of non-divergence. It has been assumed in this case that vertical motion reaches a maximum value near the 500-mb. level, so that the average through the layer below would be less than that shown on the JNWP charts. However, the JNWP values are averaged over a large horizontal area, and literature on vertical motion [3] indicates values several times the magnitude of those on the computed charts. In this investigation, since only the direction of the motion, rather than its magnitude, was important there is little loss of accuracy in using the JNWP charts.

The stability index $\overline{(\Gamma_a-\Gamma)}$ while similar to a Showalter index [4], was computed by using the point on the sound-

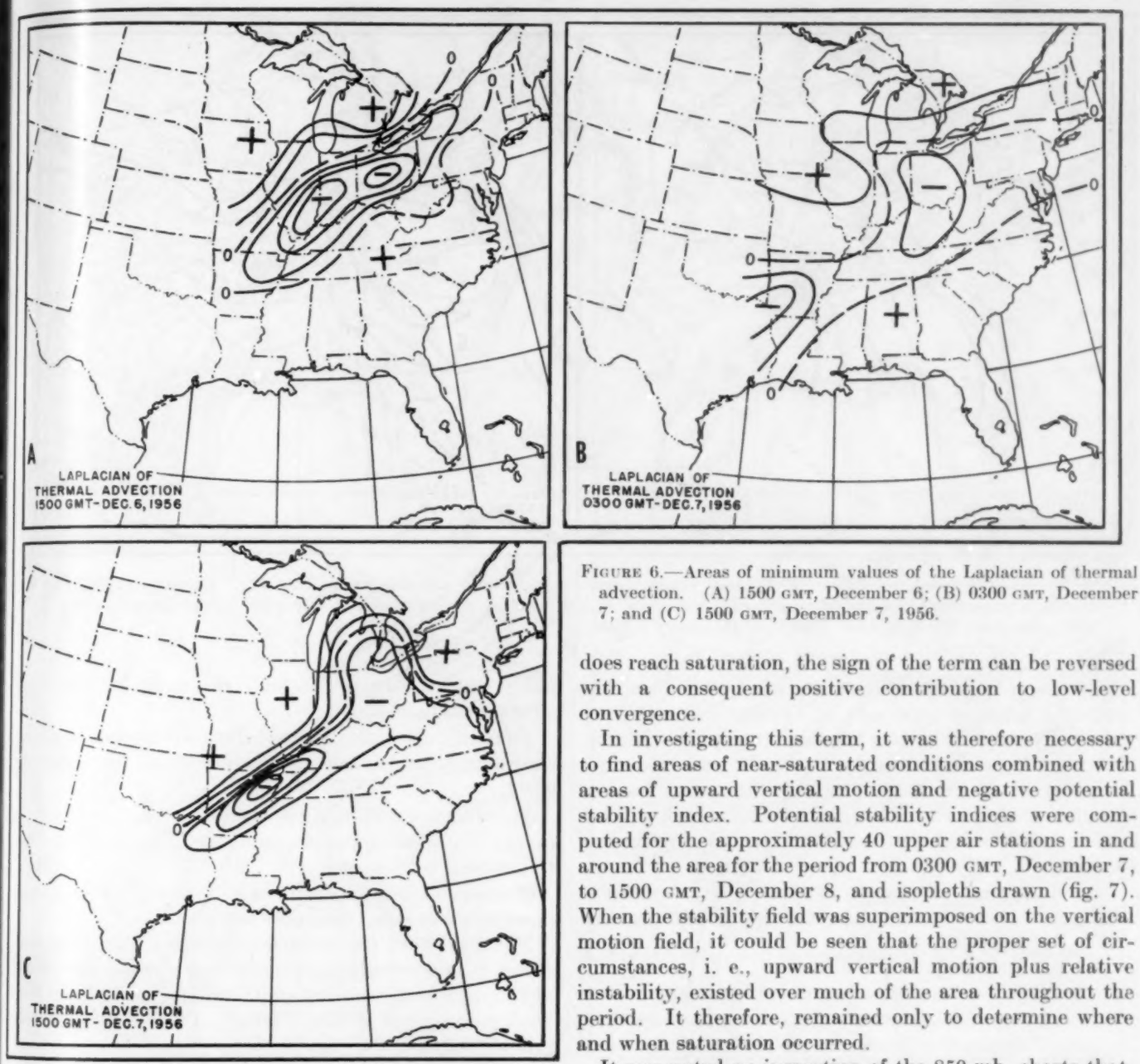

FIGURE 6.—Areas of minimum values of the Laplacian of thermal advection. (A) 1500 GMT, December 6; (B) 0300 GMT, December 7; and (C) 1500 GMT, December 7, 1956.

ing below 700 mb. which, when lifted to saturation, had a higher value of equivalent potential temperature than any other point so lifted. This index was then computed by lifting this point in the same manner as the 850-mb. point is lifted in a Showalter index.

Petterssen has shown that the sign of the entire buoyancy term is determined by whether or not the air is saturated. So long as the air remains unsaturated, any lifting will cool the air dry-adiabatically at a rate greater than the existing lapse rate. This results in the lifted air being subjected to a negative buoyancy force with respect to the ambient air, so that the term acts as a brake on the other processes. However, once the air does reach saturation, the sign of the term can be reversed with a consequent positive contribution to low-level convergence.

In investigating this term, it was therefore necessary to find areas of near-saturated conditions combined with areas of upward vertical motion and negative potential stability index. Potential stability indices were computed for the approximately 40 upper air stations in and around the area for the period from 0300 GMT, December 7, to 1500 GMT, December 8, and isopleths drawn (fig. 7). When the stability field was superimposed on the vertical motion field, it could be seen that the proper set of circumstances, i. e., upward vertical motion plus relative instability, existed over much of the area throughout the period. It therefore, remained only to determine where and when saturation occurred.

It was noted on inspection of the 850-mb. charts that, with the existing temperatures, a dew point of 10° C. over the area would result in near-saturated conditions. Study of the soundings showed that an increase of moisture occurred through a deep layer of air, at least as high as the 700-mb. level. In figure 8, the 10° C. isodrosotherm, the 850-mb. isotachs, and the axis of the maximum wind velocity at 850 mb. have been reproduced. The low-level jet carried the injection of moist air northeastward over the area. A close correlation was evident between the onset of rainfall and the time the 10° C. isodrosotherm reached a corresponding point. Several examples of this can be pointed out. Figures 8B and 8C show the 10° C. isodrosotherm progressing northeastward over southern

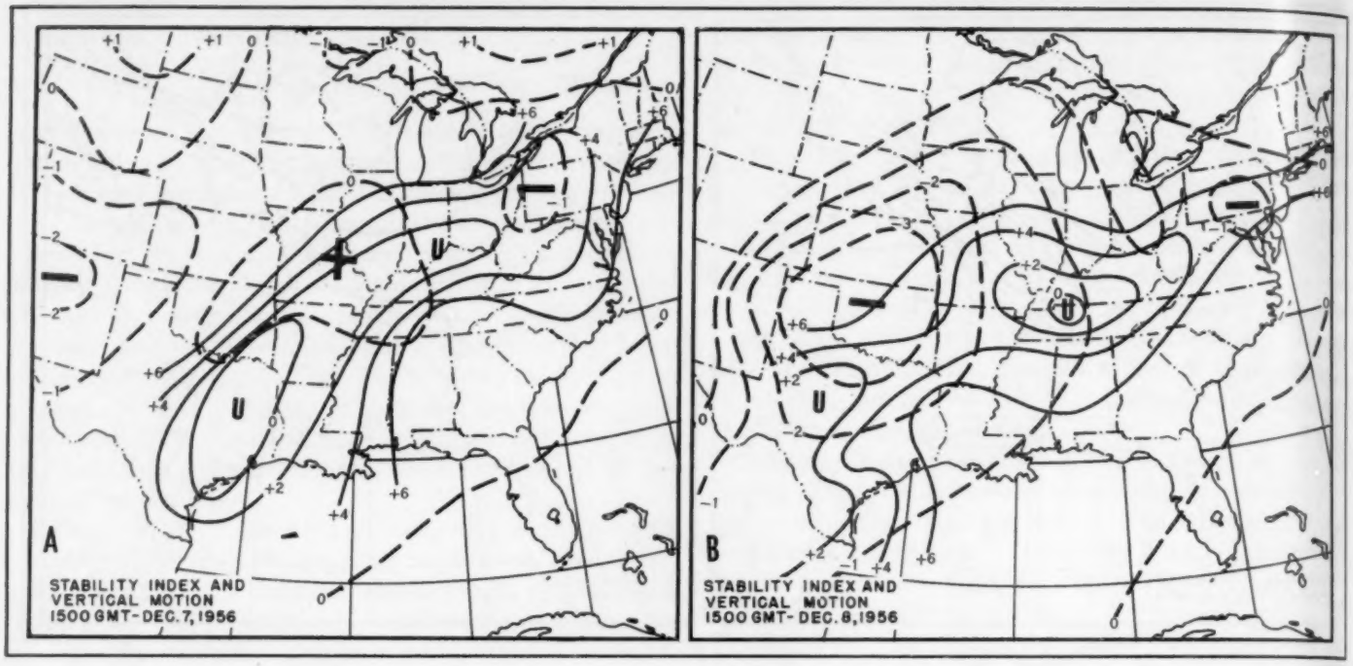

FIGURE 7.—Stability index (solid lines) with minus values indicating instability, and plus values, stability. Centers of instability are labeled U. Superimposed is the vertical motion pattern in cm/sec. (dashed lines) with minus values indicating upward motion. (A) 1500 GMT, December 7, and (B) 1500 GMT, December 8, 1956.

Missouri and southern Illinois into most of Indiana between the hours of 1500 GMT on December 6 and 0300 GMT on December 7. Rain began at Springfield, Mo. at 1700 GMT, December 6; at St. Louis, Mo. at 2100 GMT, December 6; at Ft. Wayne, and Indianapolis, Ind. at 0100 GMT, December 7. The rainfall began at each of these stations within an hour or two of the arrival of saturated conditions.

The final term of the equation is that of non-adiabatic contributions to low-level convergence, $-\frac{R}{f}\nabla^2\left[\ln\frac{p_0}{p}\frac{1}{c_p}\frac{d\overline{W}}{dt}\right]$. Petterssen has pointed out that this term is difficult to evaluate, but that statistical evidence shows it to be of importance. He also emphasizes that, by itself, the amount of heating or cooling is not important. Rather it is the configuration of the pattern of heating or cooling (i. e., the Laplacian) that determines the sign of the term and thus the sense of the contribution.

It can readily be seen that in cases of warming from below, as when a cold air mass moves over a warmer surface, there is a positive contribution to cyclonic development, while the reverse is true in an airmass being transported over a surface colder than itself.

In this case study, the air moving northeastward to the south of the front was passing over terrain of similar temperature and, consequently, was being neither cooled nor warmed from below. The southward-moving air, being relatively cold, was continually being transported over ground warmer than itself along the front. Consequently, there was a positive contribution to development along and immediately behind the front by the non-adiabatic influences.

To recapitulate, the terms of the development equation contributed to low-level convergence in the following ways:

The first term, vorticity advection at the level of non-divergence, is small, but positive in sign, thus contributing to low-level convergence.

The second term, vorticity advection at 1000 mb., was disregarded as being insignificantly small.

The third term, the Laplacian of thermal advection, was found to be generally negative in sign in areas just ahead of the cold front, thereby contributing positively to low-level convergence in those areas. There was good correlation between the negative areas of this term and areas of rainfall, both in time and space.

The fourth term, the buoyancy term, was evaluated qualitatively only, with positive contributions determined to be in regions of simultaneous occurrence of saturation, upward vertical motion, and negative potential stability index.

The correlation between time of near-saturated conditions (determined by the 10° C. isodrosotherm at 850 mb.) and the onset of rainfall was excellent. The correlation of areas of simultaneous occurrence of all three parameters mentioned above was fair to good in the early part of the period, and improved with time through the period.

The final term of the equation, relating to non-adiabatic influence, was determined to contribute positively in areas where cool air was moving over warmer terrain.

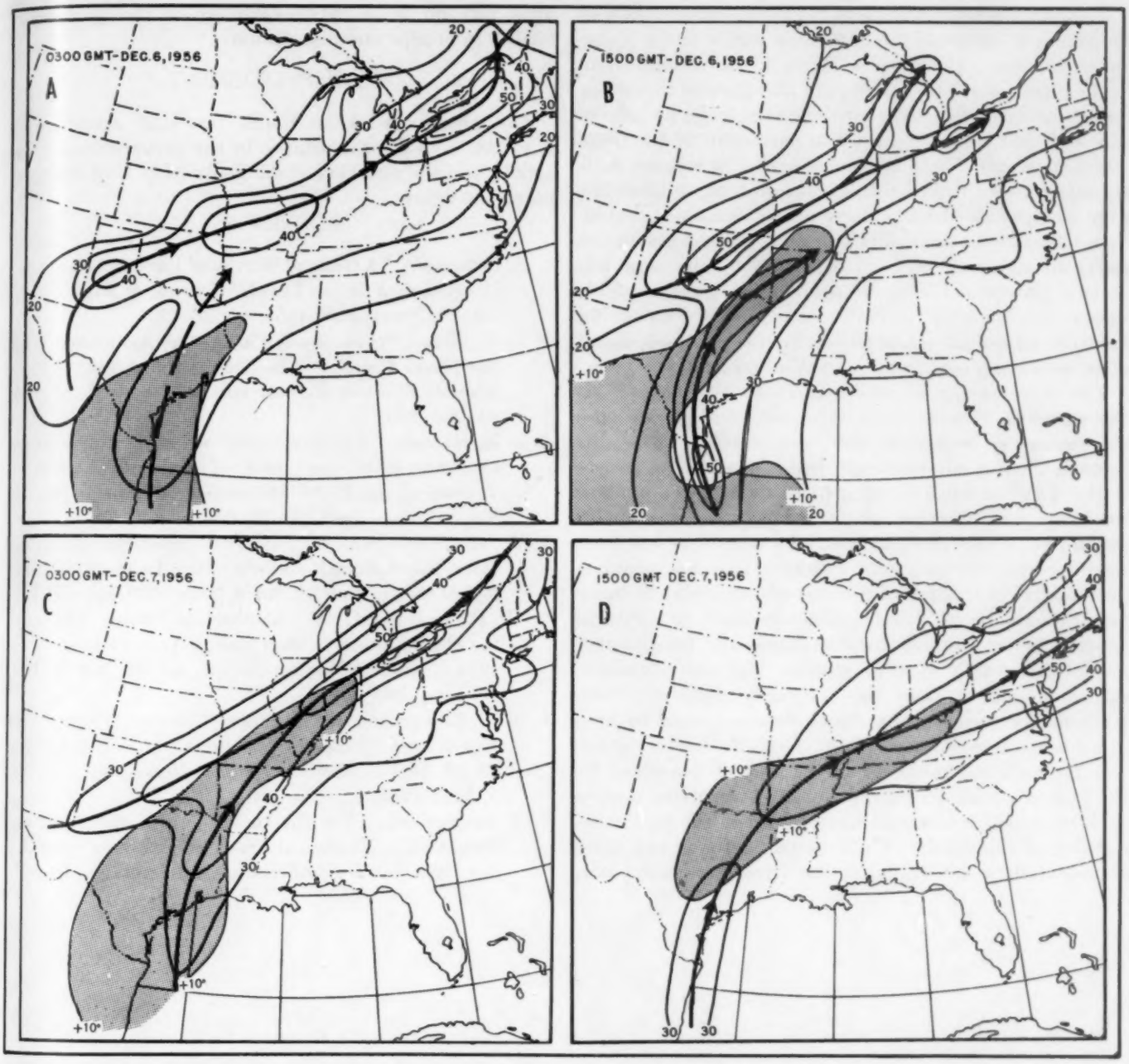

FIGURE 8.—850-mb. isotachs, maximum wind axis, and 10° C. isodrosotherm. Isotachs are labeled in knots at 10-knot invervals. Shading indicates areas where dewpoint at 850 mb. = 10° C. (A) 0300 GMT, December 6; (B) 1500 GMT, December 6; (C) 0300 GMT, December 7; and (D) 1500 GMT, December 7, 1956.

This was the case along and immediately behind the front. Ahead of the front this term could be neglected, as the air transport was over land surfaces with a nearly uniform temperature.

3. FORECASTING PROBLEM

The experienced forecaster recognizes several types of synoptic situations which produce prolonged precipitation in the Central States. One of these, a case of heavy thunderstorms in the warm air south of a front, has been studied by Means [2], and Nash and Chamberlain [5]. Oliver and Shaw [6] have studied a case of heavy warm-sector rains, while the situation described here involves precipitation closely related to a slow-moving cold front. To produce a satisfactory forecast in this case, the forecaster would have had to anticipate the slow speed of the frontal movement, the instability of the warm air ahead of the front, and the increase of moisture in the warm air.

Probably the key influence on the frontal movement was the stagnant nature of the large-scale waves in the upper air circulation. As shown in figure 3, the 500-mb. flow in the region of study was straight and parallel to the sea level front; therefore the contribution of vorticity advection aloft was insignificant. The movement of the front was then mainly due to low-level forces. It was not until an upper trough moved through the area (fig. 5) that the front changed its speed or shape to any significant degree.

In this case the instability and moisture increase in the warm air ahead of the front developed by the usual advective process. This is illustrated in figure 8 which shows the low-level wind increase and accompanying moisture advection characteristic to the air mass ahead of an advancing cold front in the Central States.

The question can be asked, given a situation such as this where the synoptic features are not unusual, how does the forecaster determine that precipitation will result in more than usual amounts? Unfortunately the answer to this question has been suggested here only in a qualitative way. The portion of this study which dealt with evaluation of the physical processes related to low-level convergence (precipitation) indicates that no complete quantitative evaluation of Petterssen's equation can come from that approach. It is hoped new research (c. f. [7]) will produce better methods for computing and interrelating precipitation with vertical motion, thermal advection, saturation effects, and the buoyancy features. Such methods are needed before those elements could be used in a routine forecast procedure. Even the present available methods are hampered in the area of this study by the lack of upper air observations. A reporting station at Evansville, Ind. would have added much to the reliability of this study. Until better methods and more abundant data are available, the forecaster, it appears, must rely on qualitative evaluation of the parameters related to precipitation formation.

ACKNOWLEDGMENT

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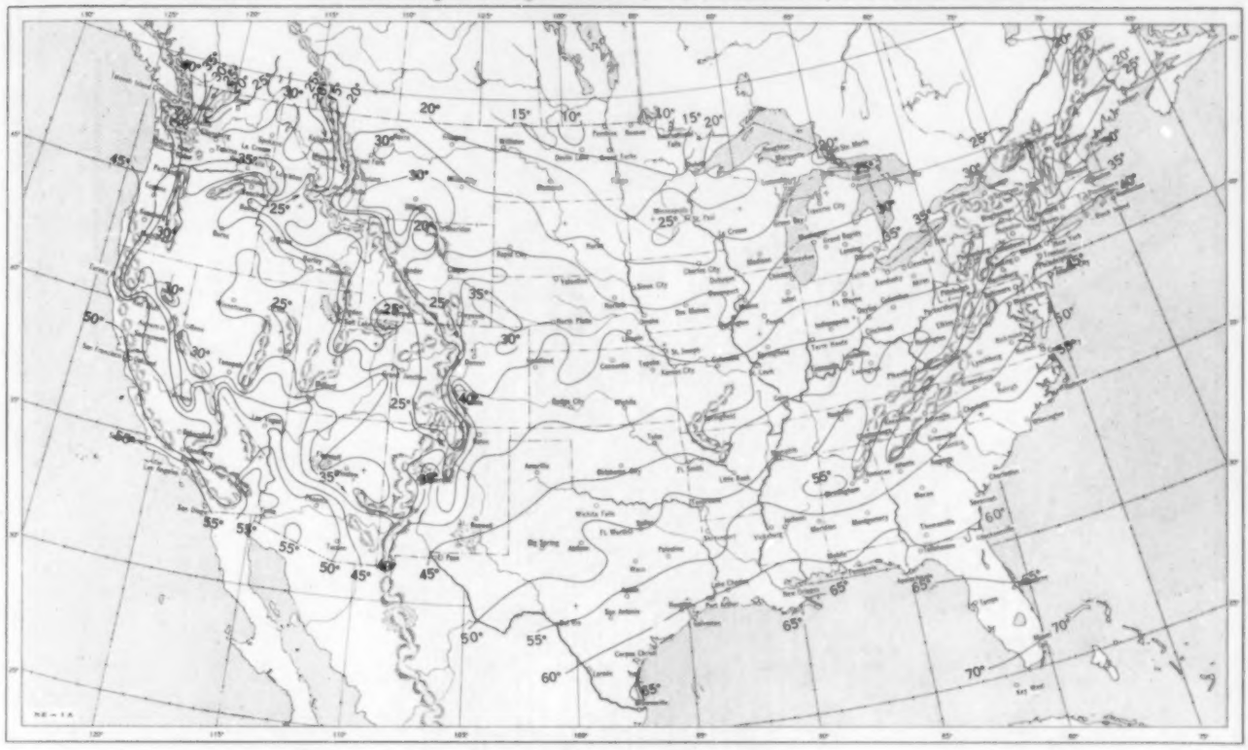
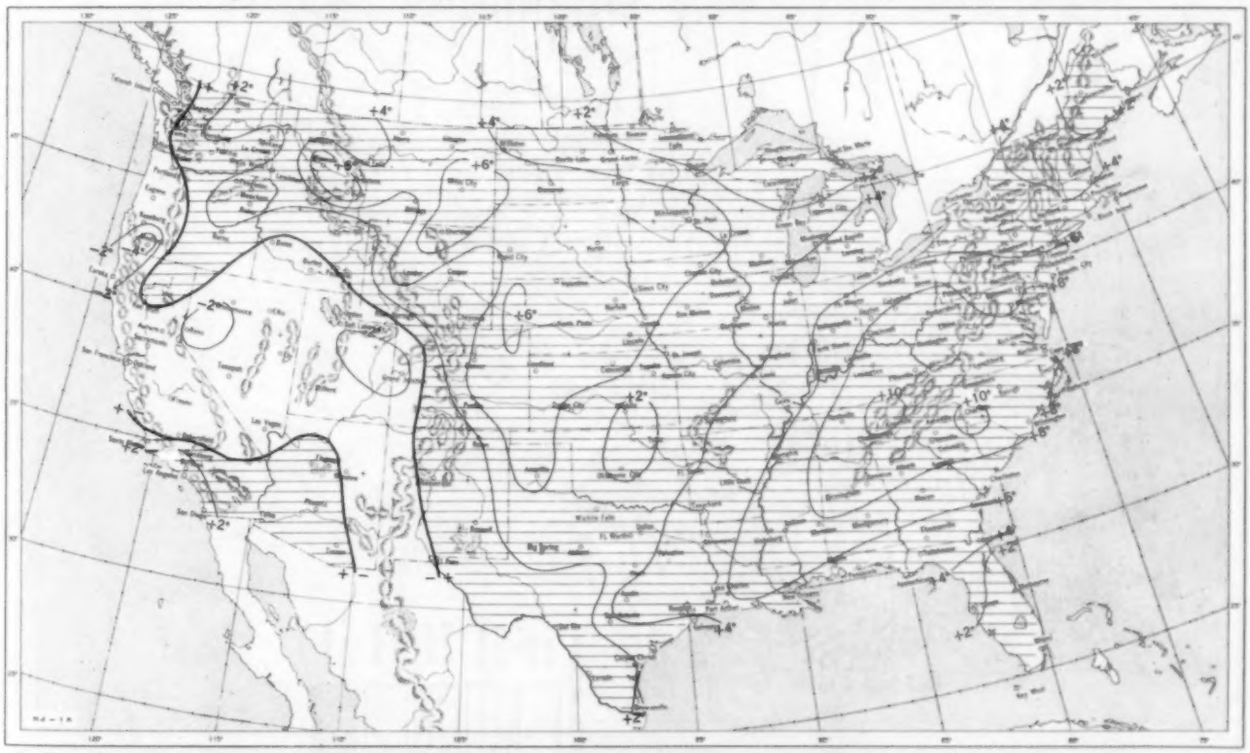
U. S. GOVERNMENT PRINTING OFFICE: 1957

Chart I. A. Average Temperature (°F.) at Surface, December 1956.

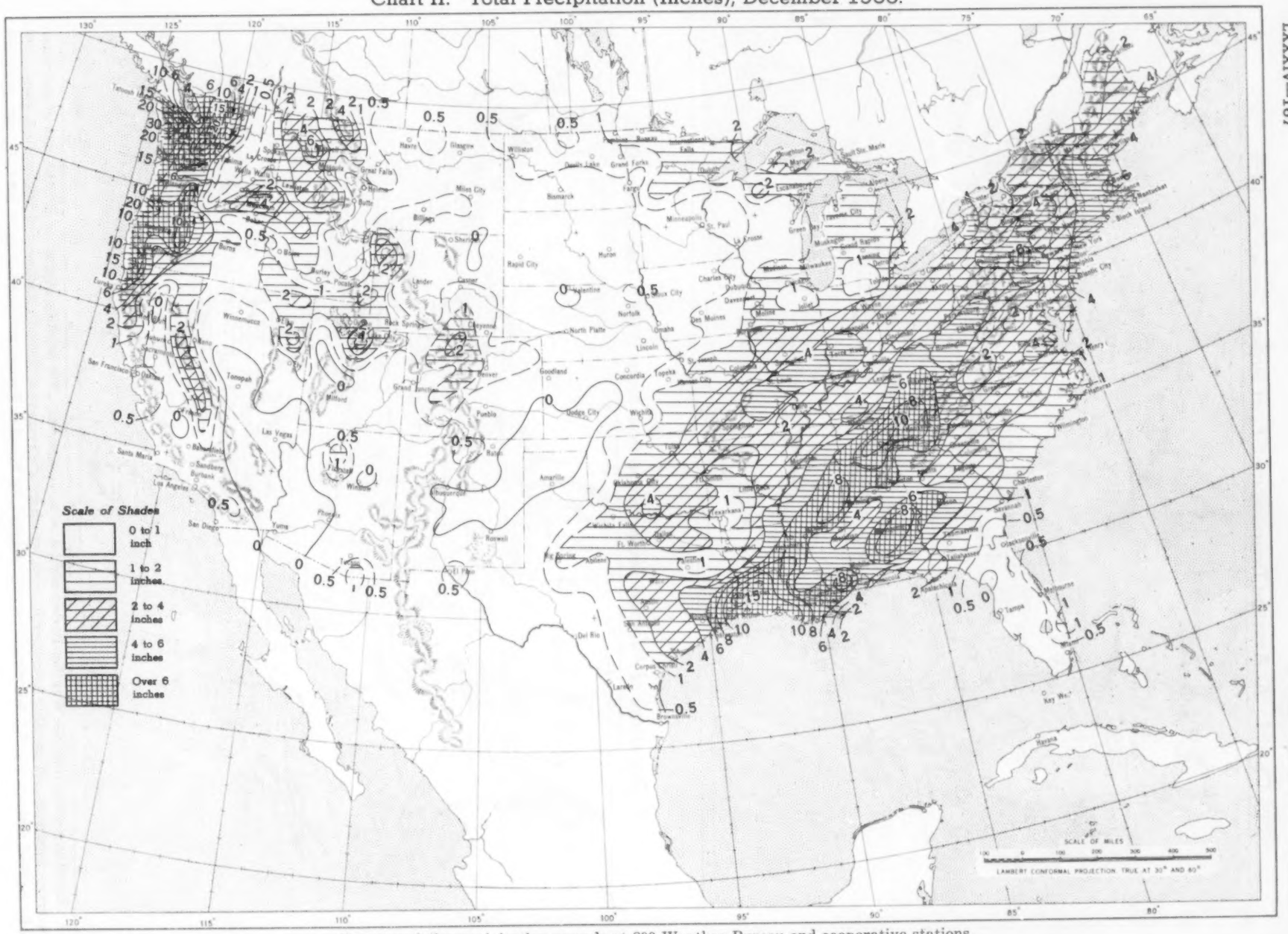


B. Departure of Average Temperature from Normal (°F.), December 1956.



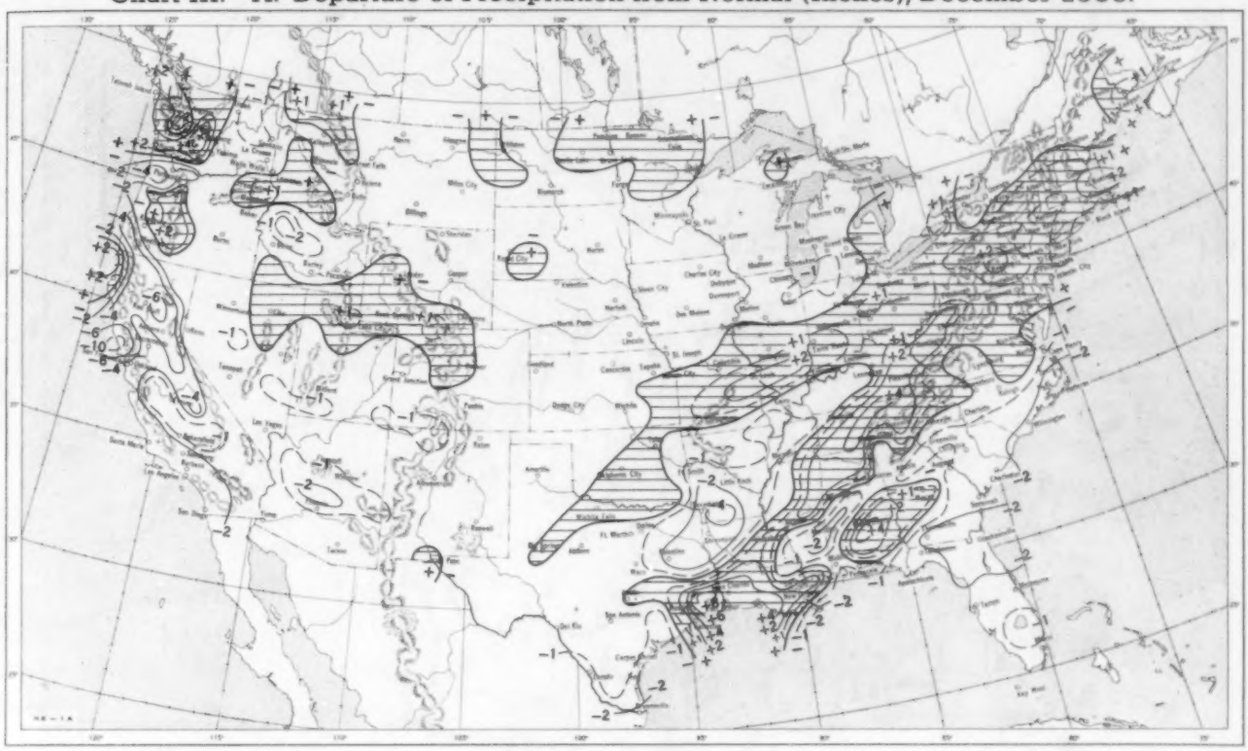
A. Based on reports from 800 Weather Bureau and cooperative stations. The monthly average is half the sum of the monthly average maximum and monthly average minimum, which are the average of the daily maxima and daily minima, respectively.
B. Normal average monthly temperatures are computed for Weather Bureau stations having at least 10 years of record.

Chart II. Total Precipitation (Inches), December 1956.

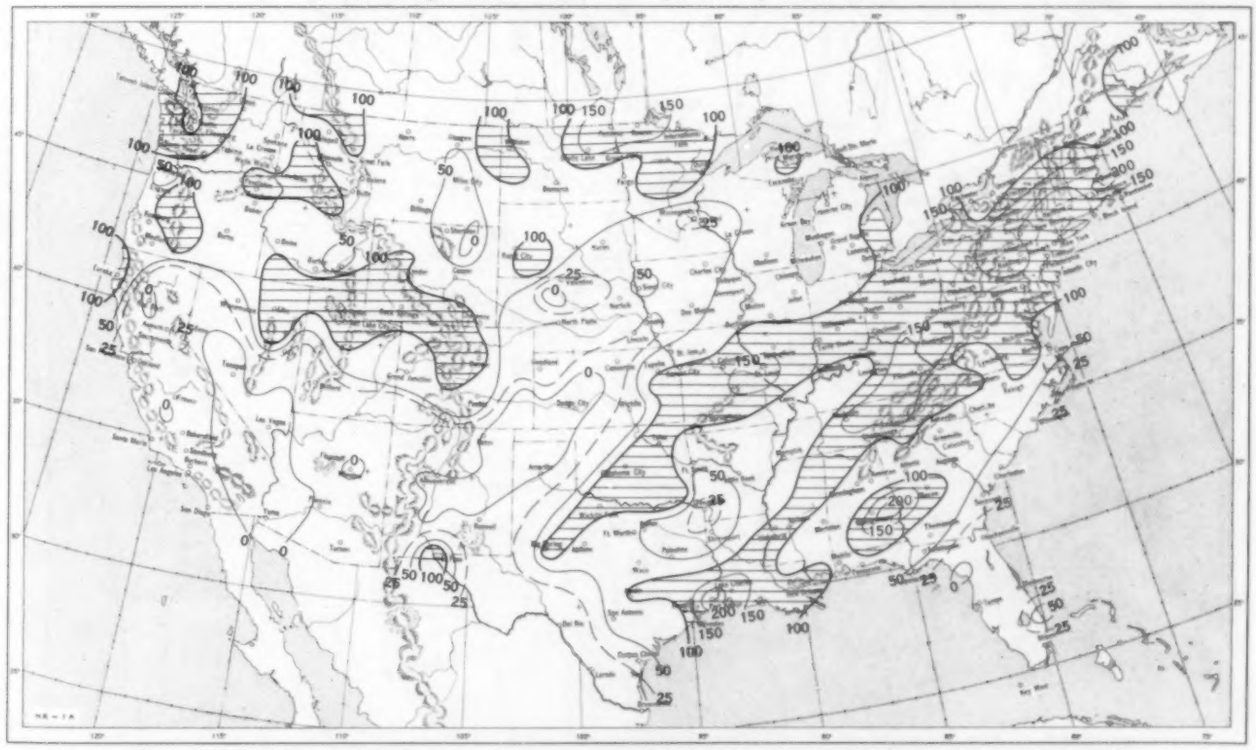

Scale of Shades
0 to 1 inch
1 to 2 inches
2 to 4 inches
4 to 6 inches
Over 6 inches
SCALE OF MILES
LAMBERT CONFORMAL PROJECTION TRUE AT 30° AND 60°

Based on daily precipitation records at 800 Weather Bureau and cooperative stations.

Chart III. A. Departure of Precipitation from Normal (Inches), December 1956.

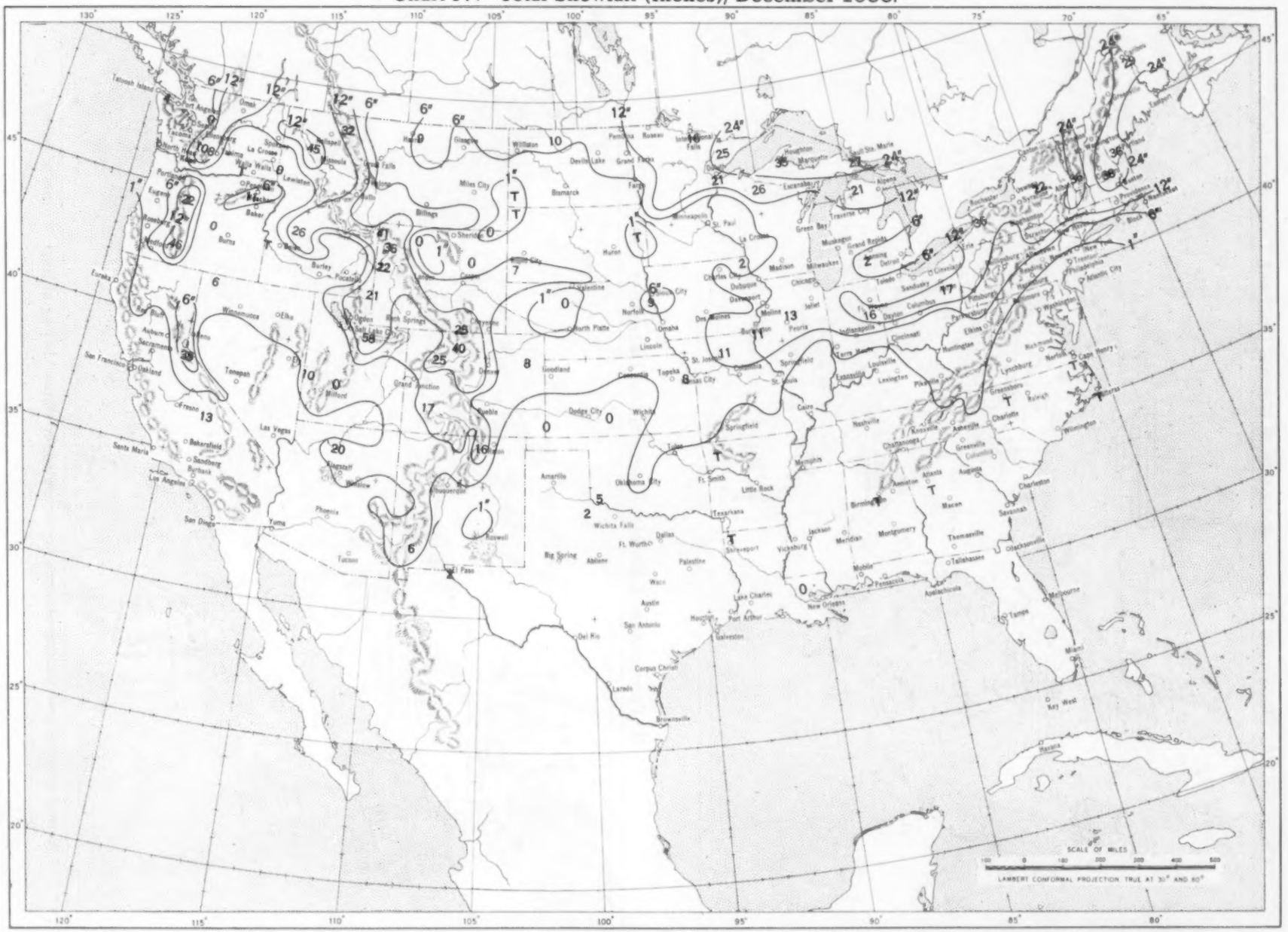


B. Percentage of Normal Precipitation, December 1956.



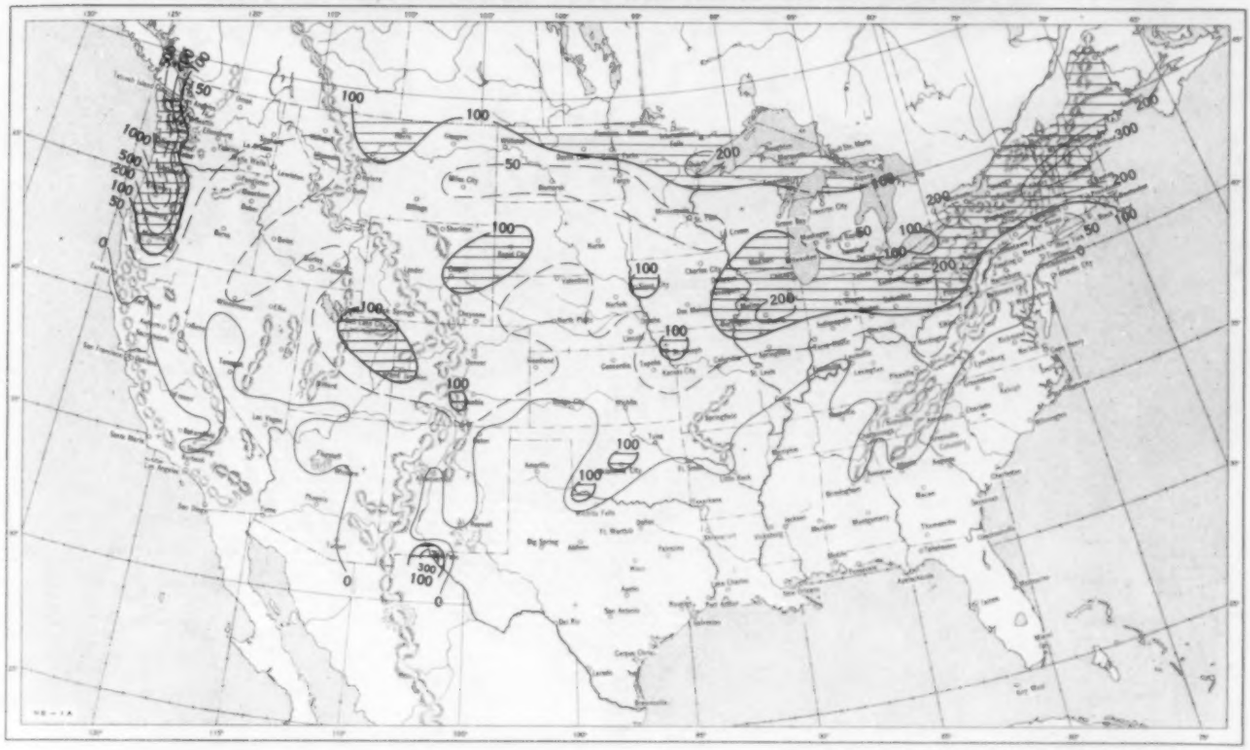
Normal monthly precipitation amounts are computed for stations having at least 10 years of record.

Chart IV. Total Snowfall (Inches), December 1956.

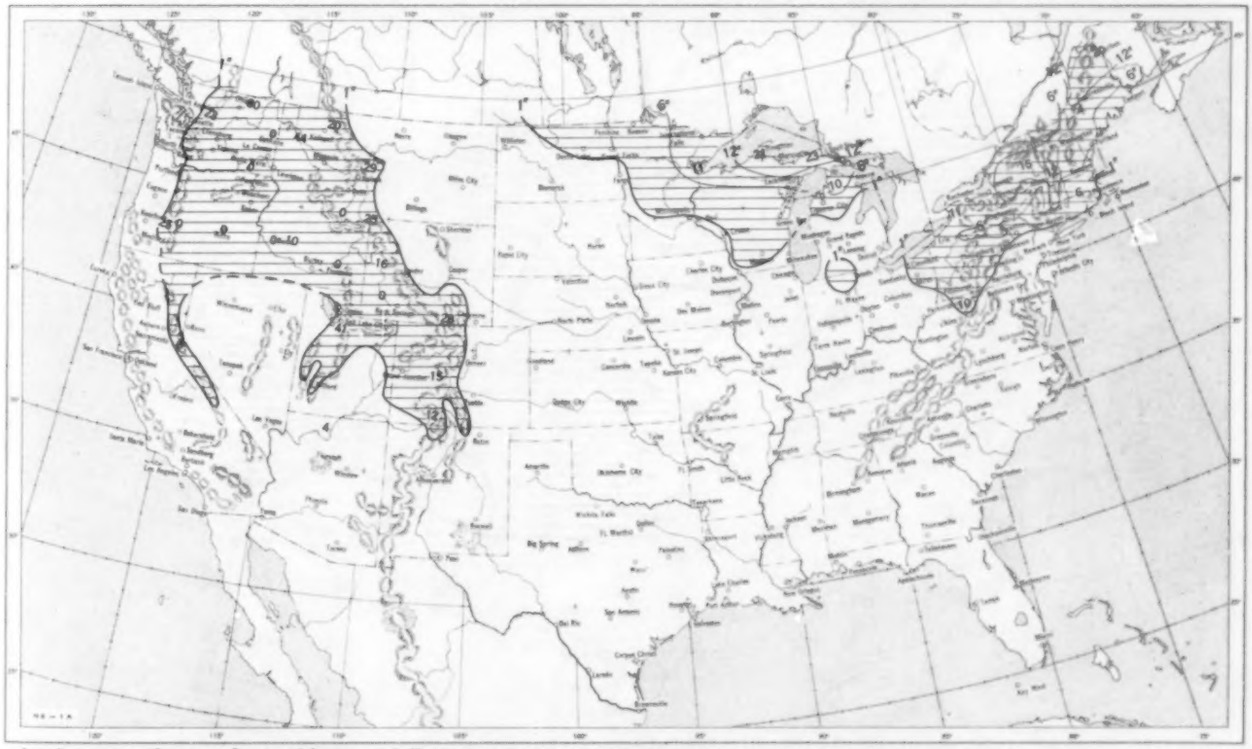


This is the total of unmelted snowfall recorded during the month at Weather Bureau and cooperative stations. This chart and Chart V are published only for the months of November through April although of course there is some snow at higher elevations, particularly in the far West, earlier and later in the year.

Chart V. A. Percentage of Normal Snowfall, December 1956.

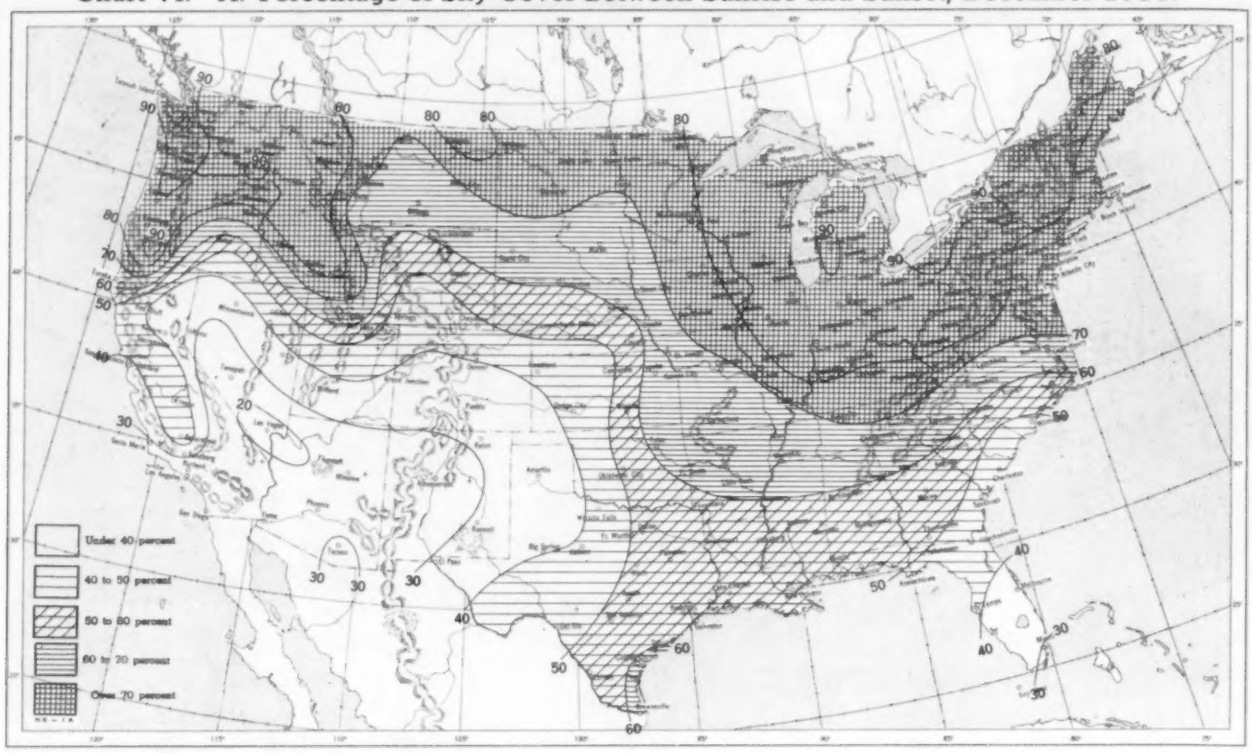


B. Depth of Snow on Ground (Inches). 7:30 a. m. E. S. T., December 31, 1956.

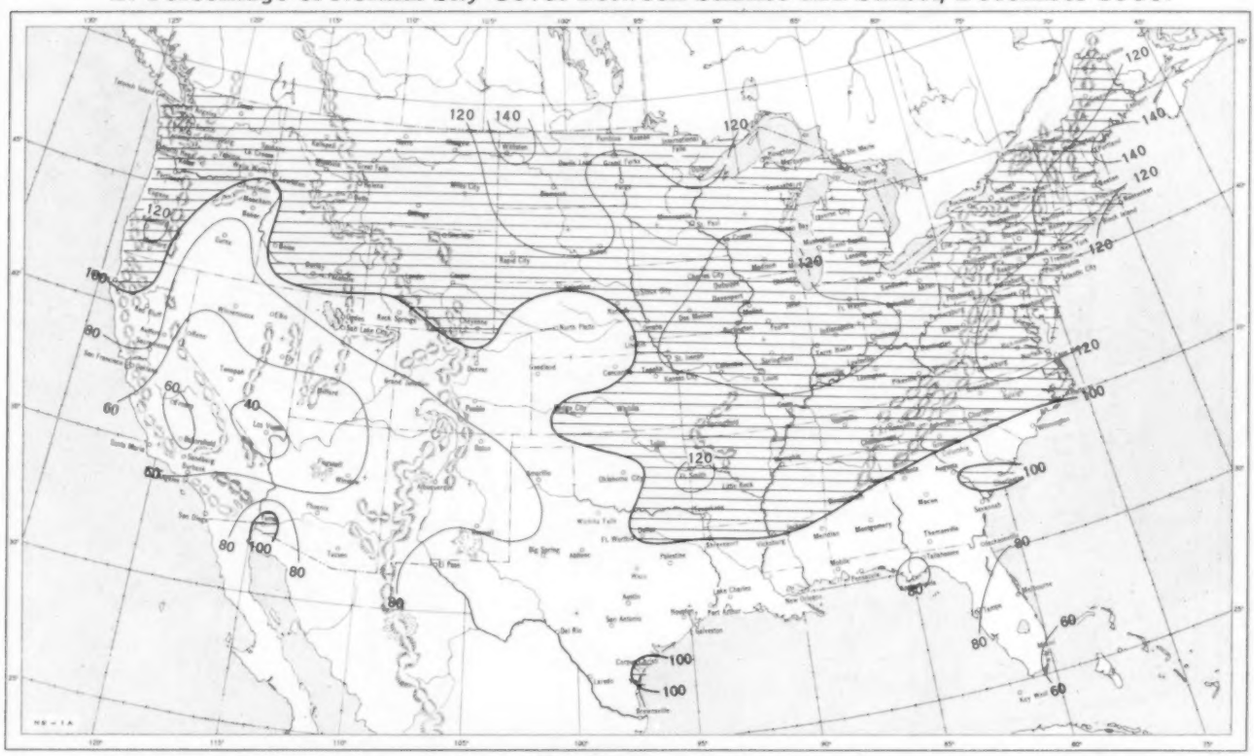


A. Amount of normal monthly snowfall is computed for Weather Bureau stations having at least 10 years of record.
B. Shows depth currently on ground at 7:30 a. m. E. S. T., of the Tuesday nearest the end of the month. It is based on reports from Weather Bureau and cooperative stations. Dashed line shows greatest southern extent of snowcover during month.

Chart VI. A. Percentage of Sky Cover Between Sunrise and Sunset, December 1956.

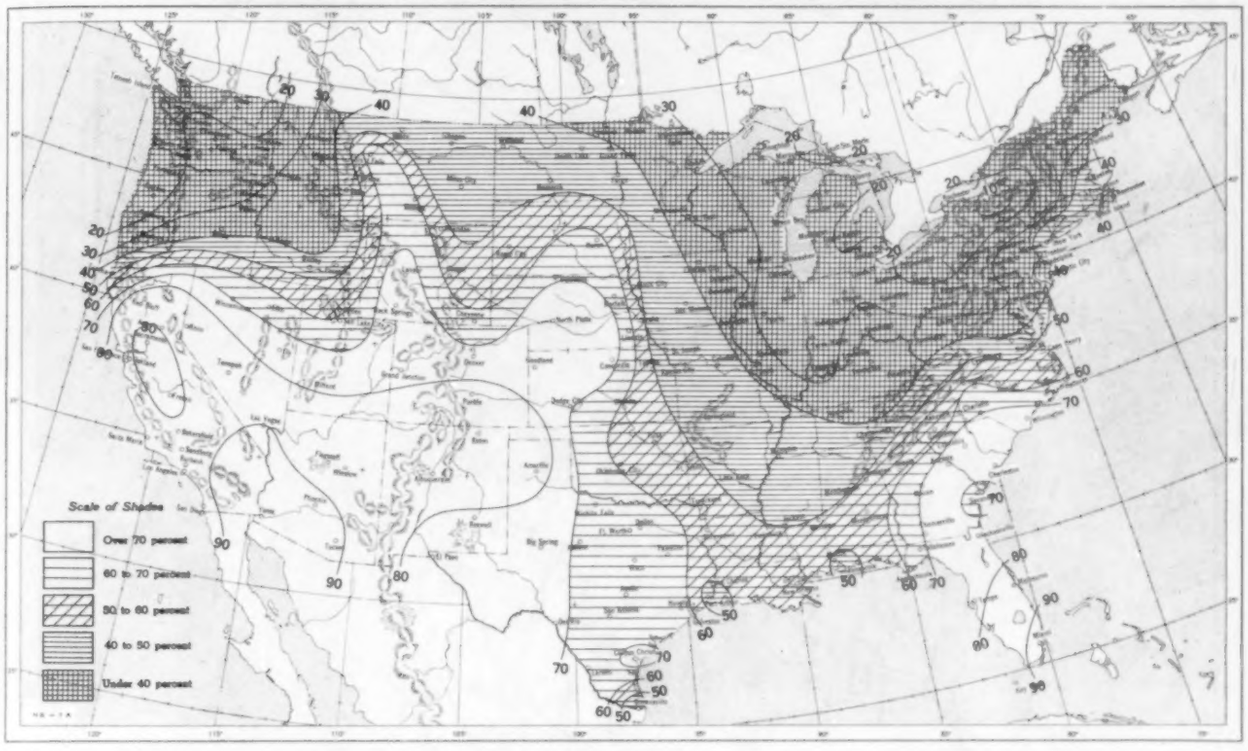


B. Percentage of Normal Sky Cover Between Sunrise and Sunset, December 1956.

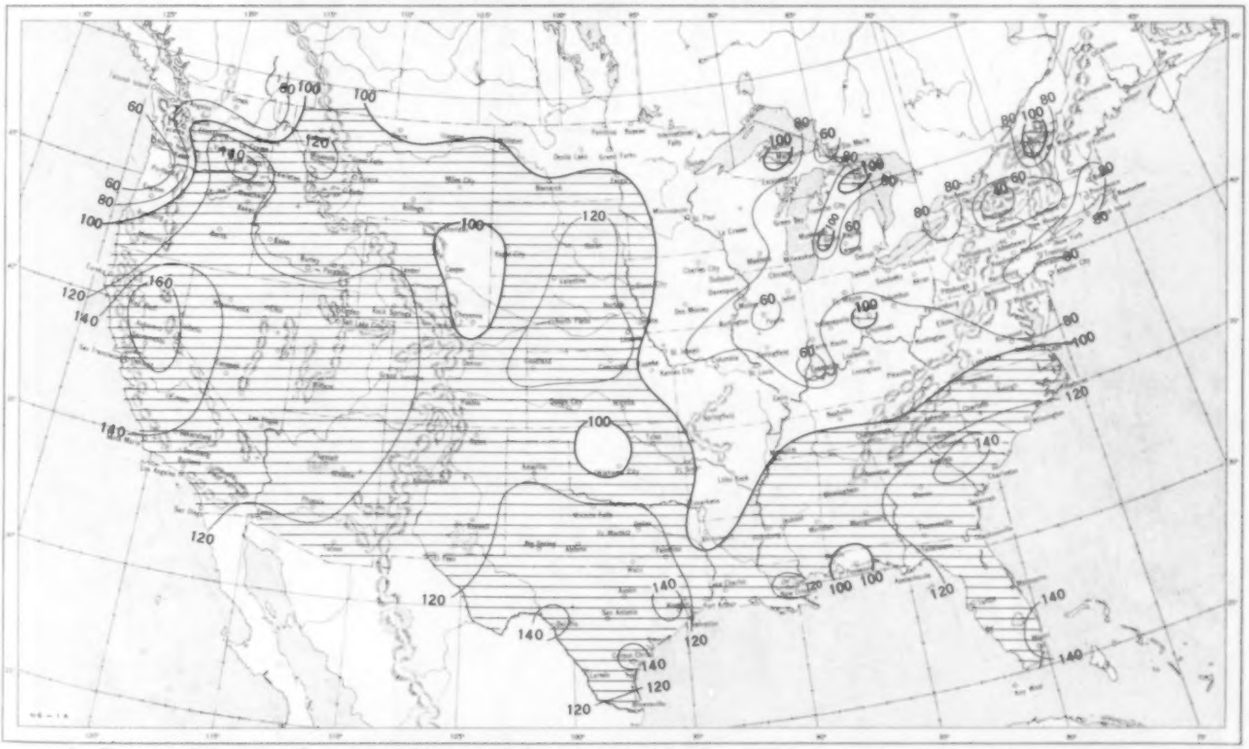


A. In addition to cloudiness, sky cover includes obscuration of the sky by fog, smoke, snow, etc. Chart based on visual observations made hourly at Weather Bureau stations and averaged over the month. B. Computations of normal amount of sky cover are made for stations having at least 10 years of record.

Chart VII. A. Percentage of Possible Sunshine, December 1956.



B. Percentage of Normal Sunshine, December 1956.



A. Computed from total number of hours of observed sunshine in relation to total number of possible hours of sunshine during month. B. Normals are computed for stations having at least 10 years of record.

Chart VIII. Average Daily Values of Solar Radiation, Direct + Diffuse, December 1956. Inset: Percentage of Mean Daily Solar Radiation, December 1956. (Mean based on period 1951-55.)

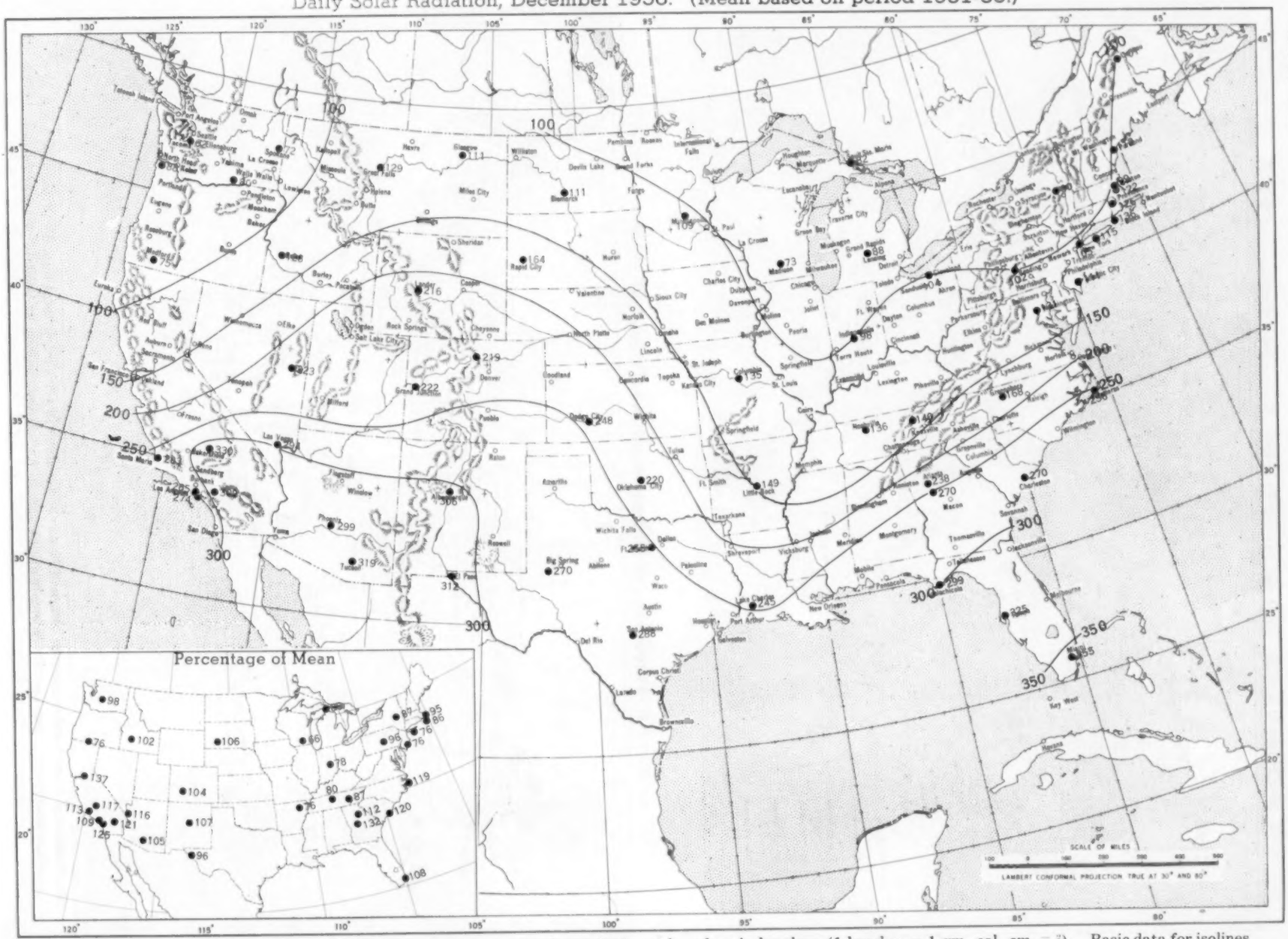
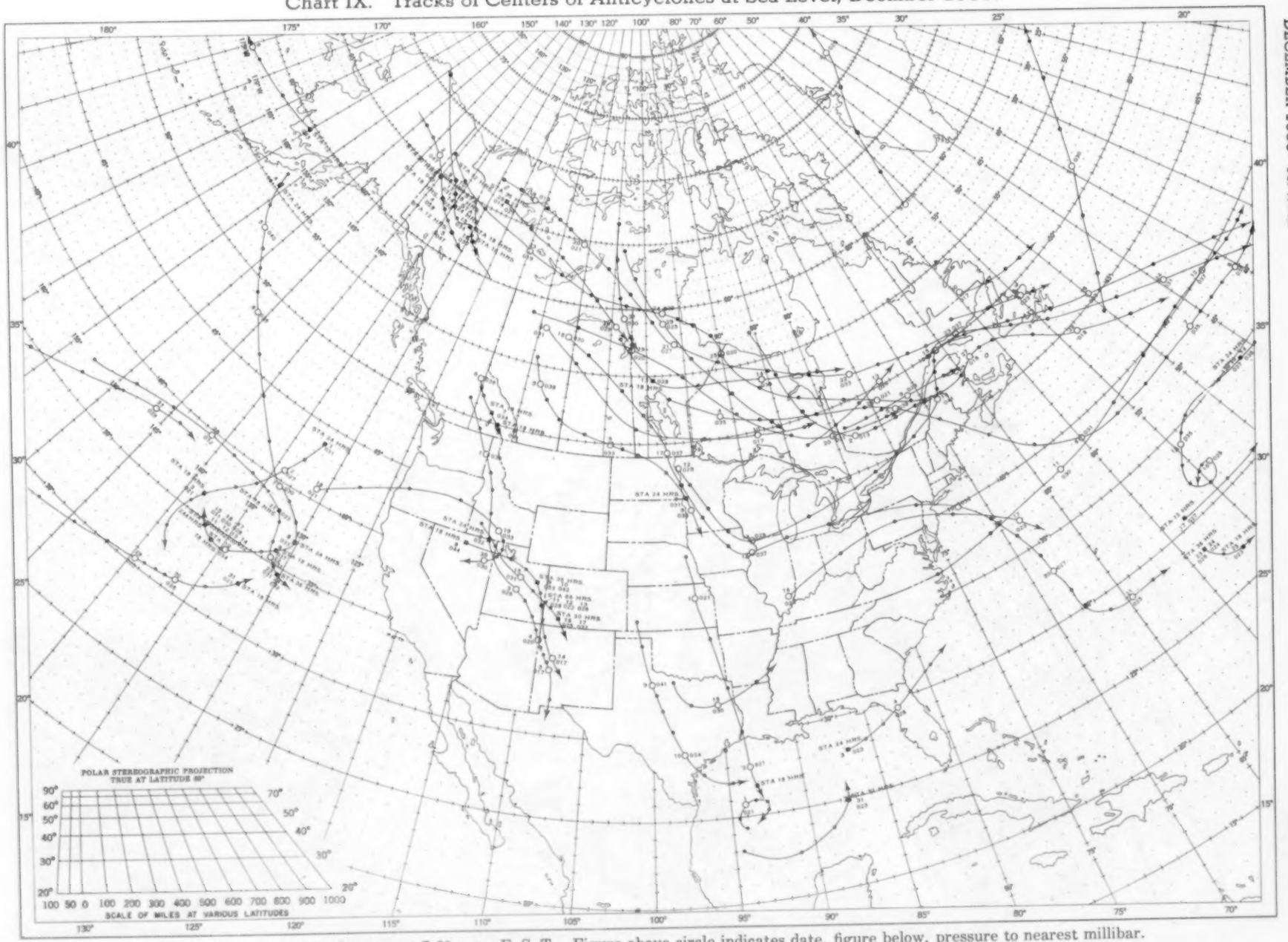


Chart shows mean daily solar radiation, direct + diffuse, received on a horizontal surface in langleys (1 langley = 1 gm. cal. cm. $^{-2}$). Basic data for isolines are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

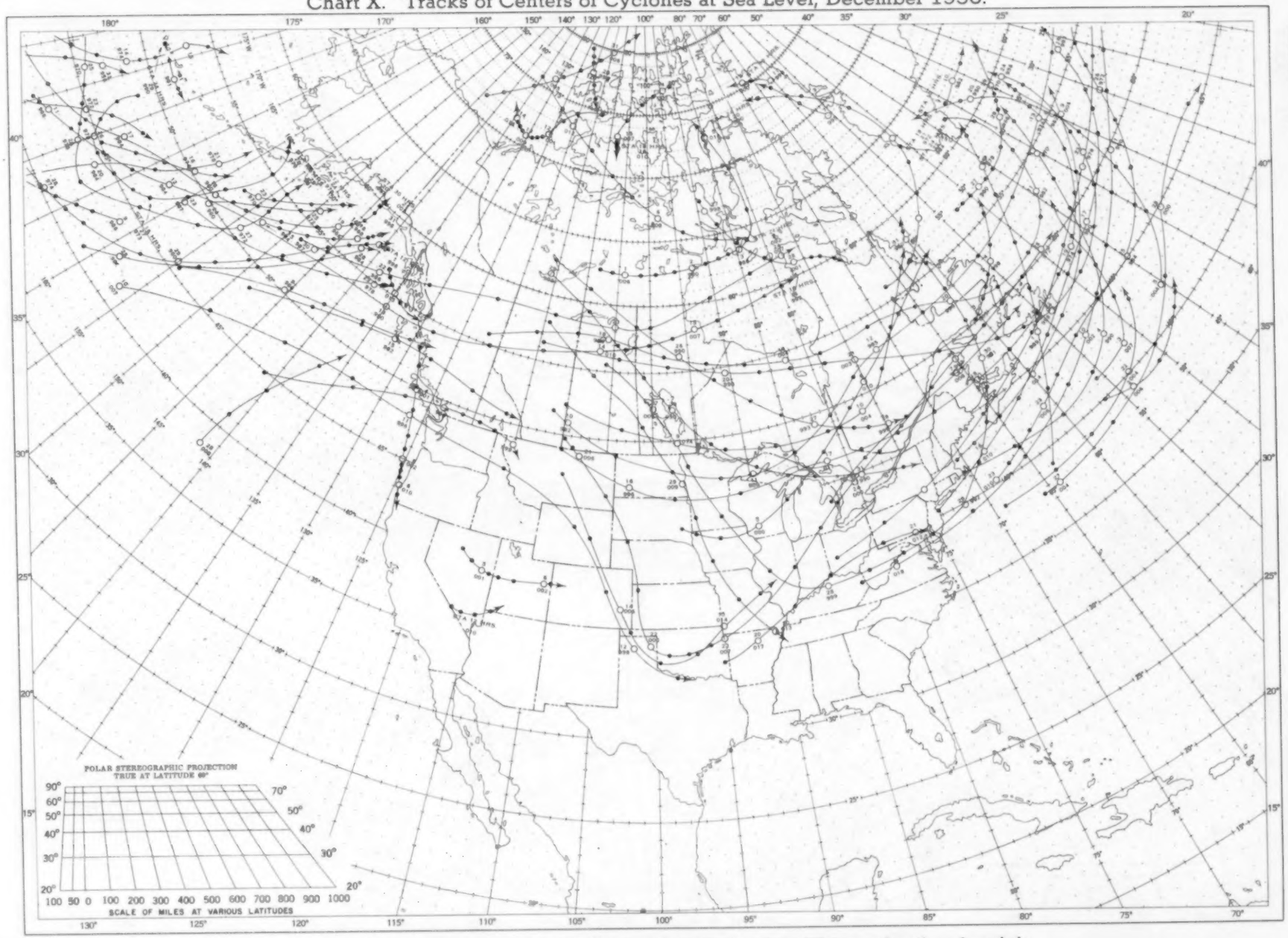
are shown on chart. Further estimates are obtained from supplementary data for which limits of accuracy are wider than for those data shown.

Chart IX. Tracks of Centers of Anticyclones at Sea Level, Decmber 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

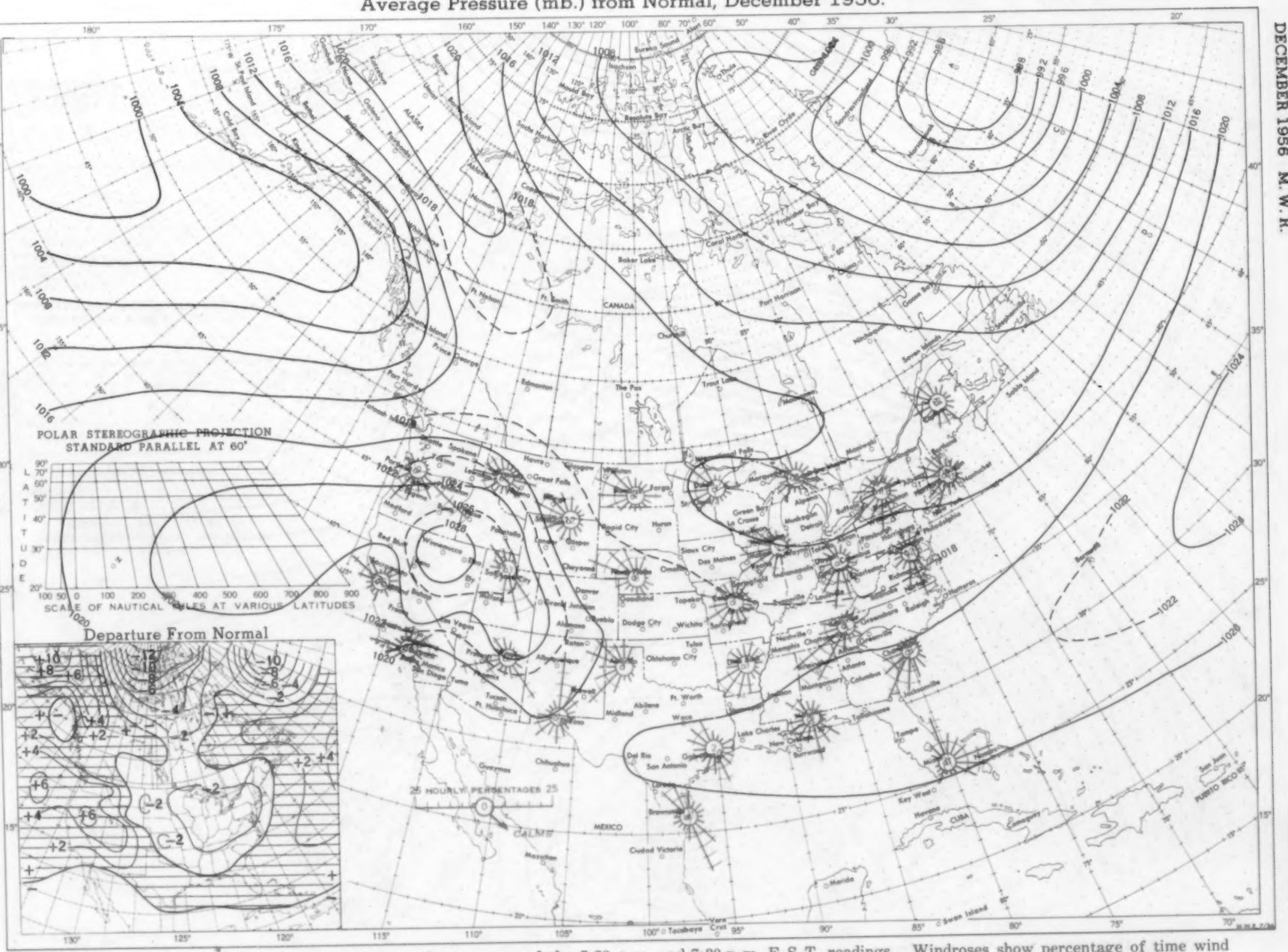
Circle indicates position of center at 7:30 a. m. E. S. T. Figure above circle indicates date, figure below, pressure to nearest millibar. Dots indicate intervening 6-hourly positions. Squares indicate position of stationary center for period shown. Dashed line in track indicates reformation at new position. Only those centers which could be identified for 24 hours or more are included.

Chart X. Tracks of Centers of Cyclones at Sea Level, December 1956.


POLAR STEREOGRAPHIC PROJECTION
TRUE AT LATITUDE 60°
90° 60° 50° 40° 30° 20°
70° 50° 40° 30° 20°
100 50 0 100 200 300 400 500 600 700 800 900 1000
SCALE OF MILES AT VARIOUS LATITUDES

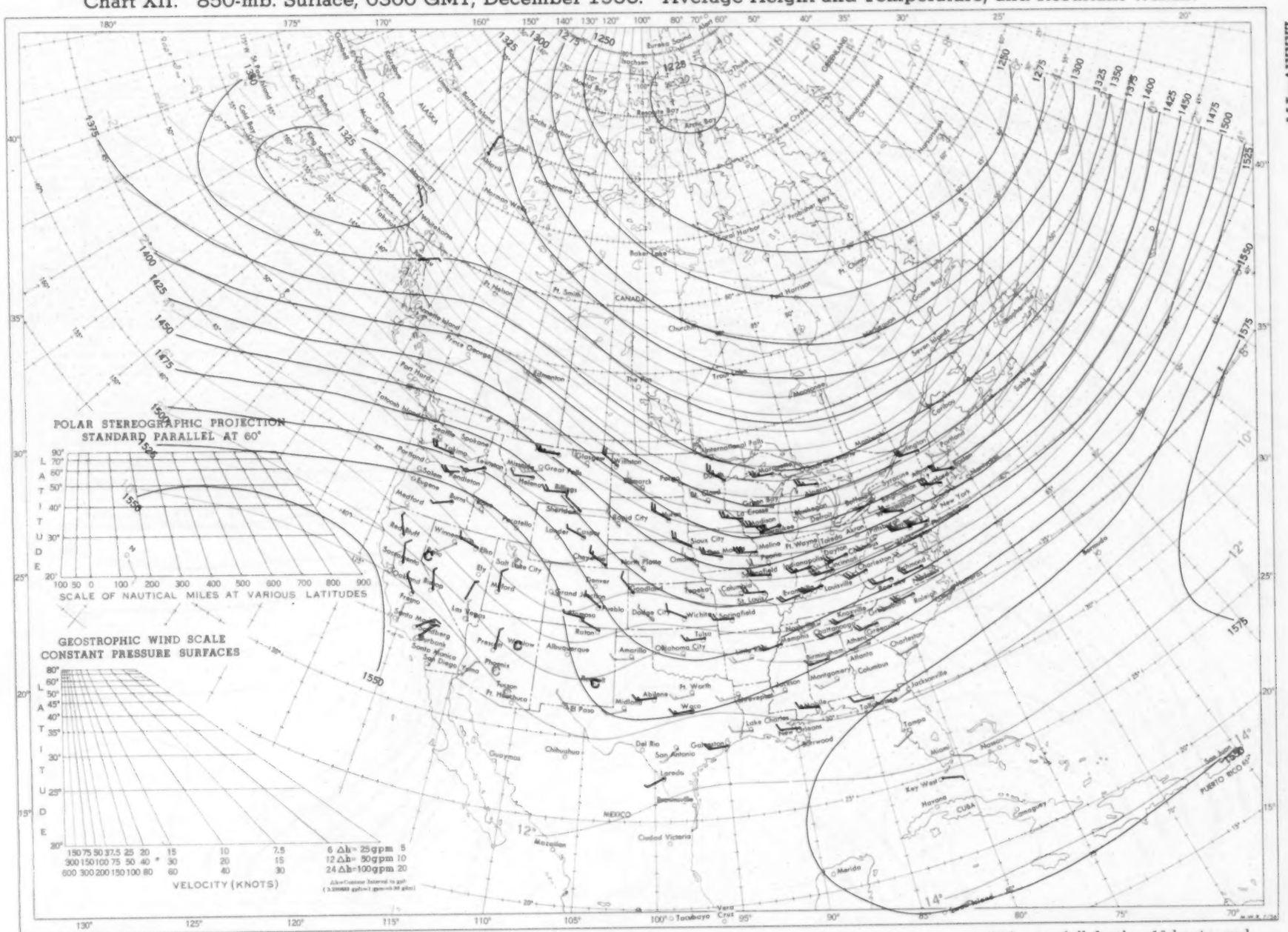
Circle indicates position of center at 7:30 a. m. E. S. T. See Chart IX for explanation of symbols.

Chart XI. Average Sea Level Pressure (mb.) and Surface Windroses, December 1956. Inset: Departure of Average Pressure (mb.) from Normal, December 1956.



Average sea level pressures are obtained from the averages of the 7:30 a. m. and 7:30 p. m. E. S. T. readings. Windroses show percentage of time wind blew from 16 compass points or was calm during the month. Pressure normals are computed for stations having at least 10 years of record and for 10° intersections in a diamond grid based on readings from the Historical Weather Maps (1899-1939) for the 20 years of most complete data coverage prior to 1940.

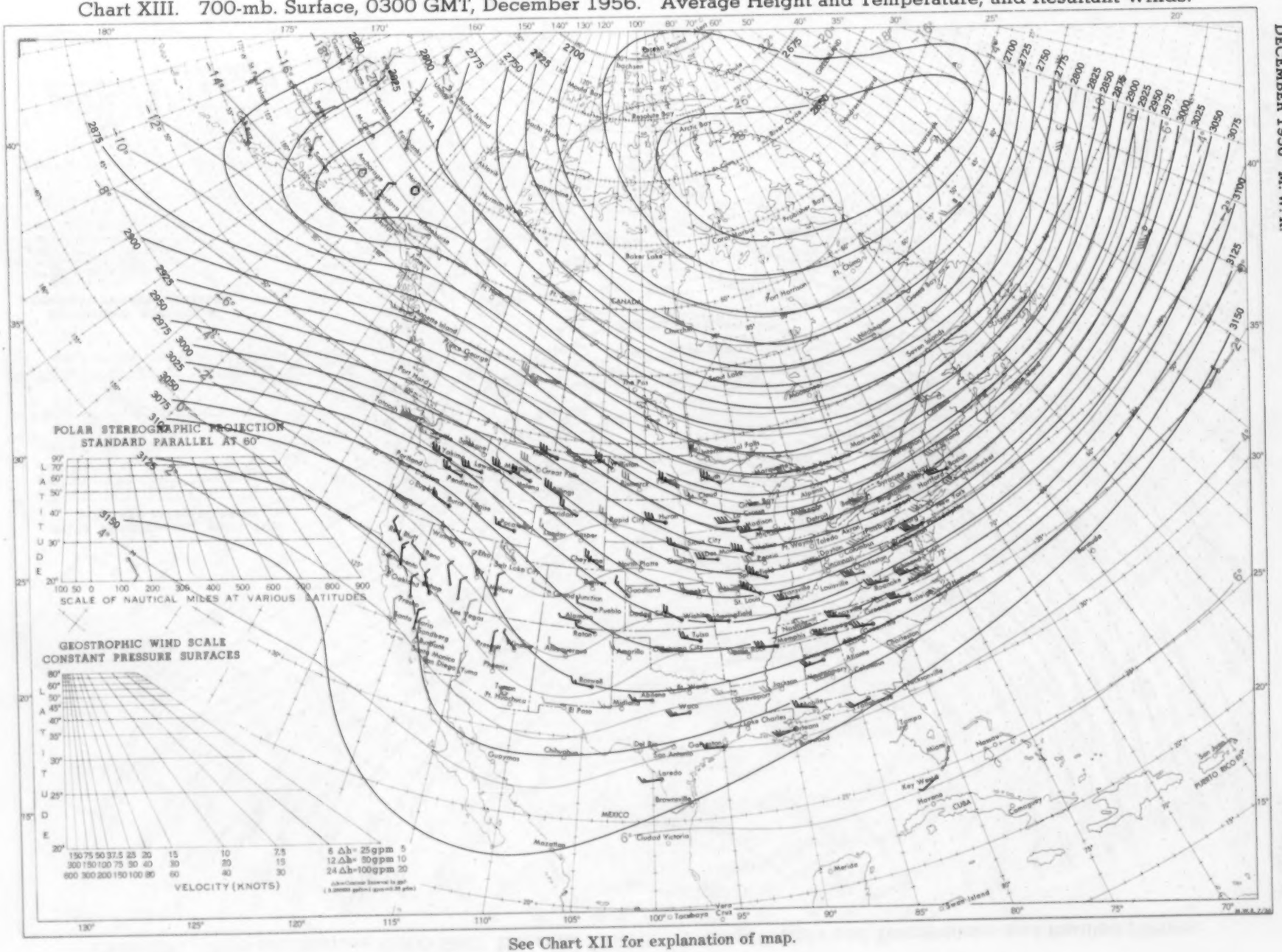
Chart XII. 850-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



Height in geopotential meters (1 g.p.m. = 0.98 dynamic meters). Temperature in °C. Wind speed in knots; flag represents 50 knots, full feather 10 knots, and half feather 5 knots. Winds shown in red are based on rawins taken at the indicated pressure surface and time. Those in black are based on pibals taken at 2100 GMT and are for the nearest standard height level.

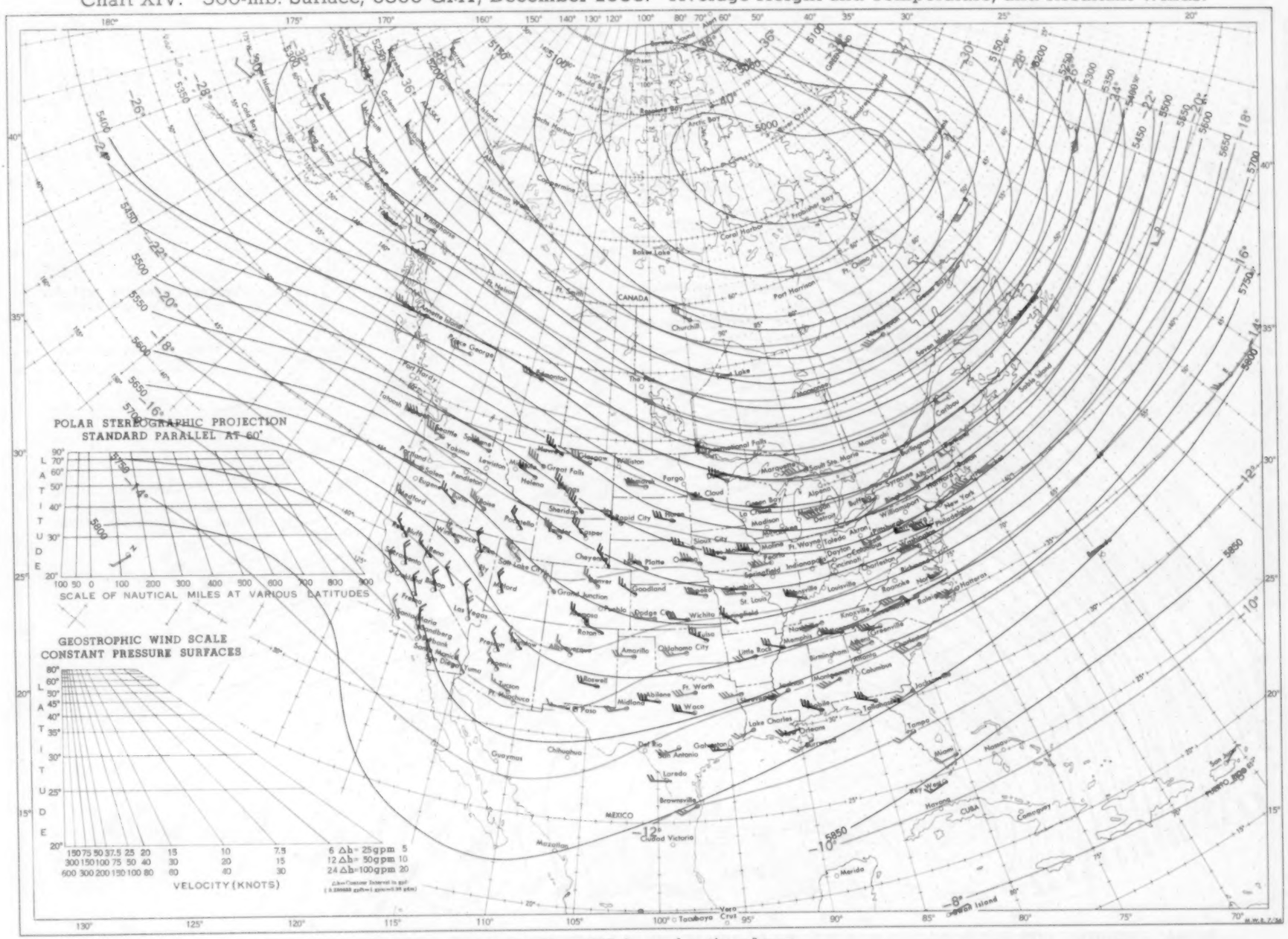
on pibals taken at 2100 GMT and are for the nearest standard height level.

Chart XIII. 700-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



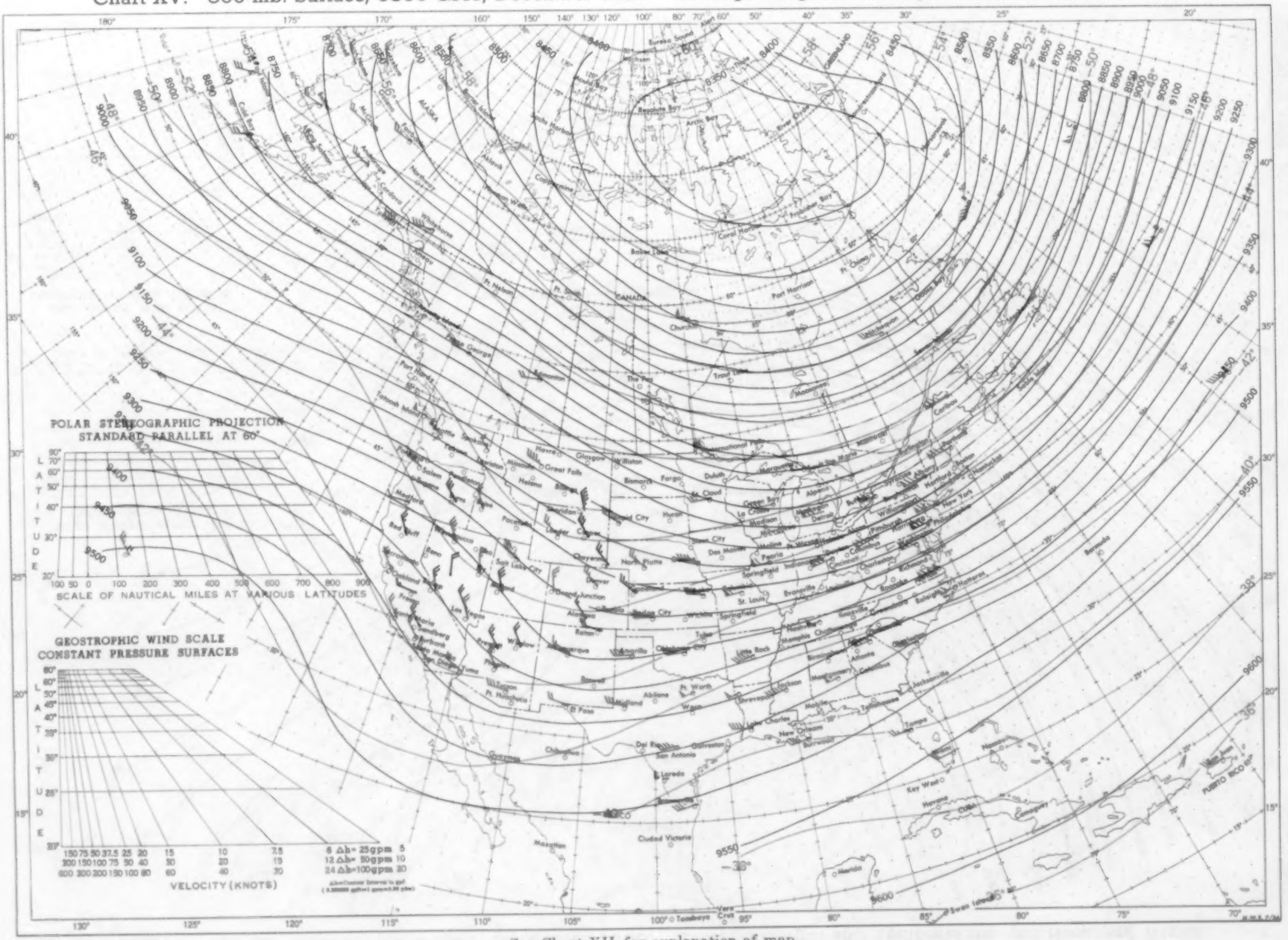
See Chart XII for explanation of map.

Chart XIV. 500-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



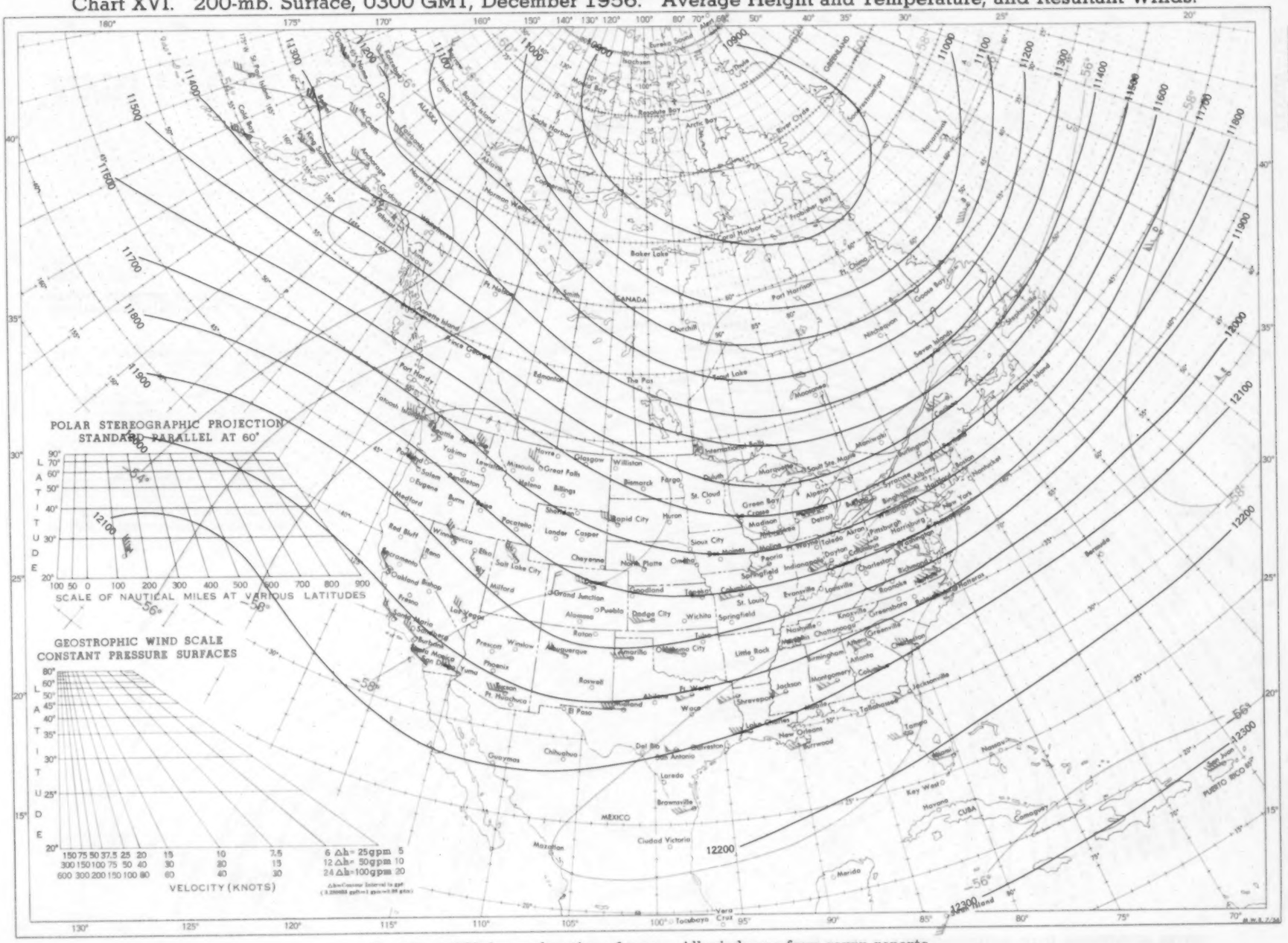
See Chart XII for explanation of map.

Chart XV. 300-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



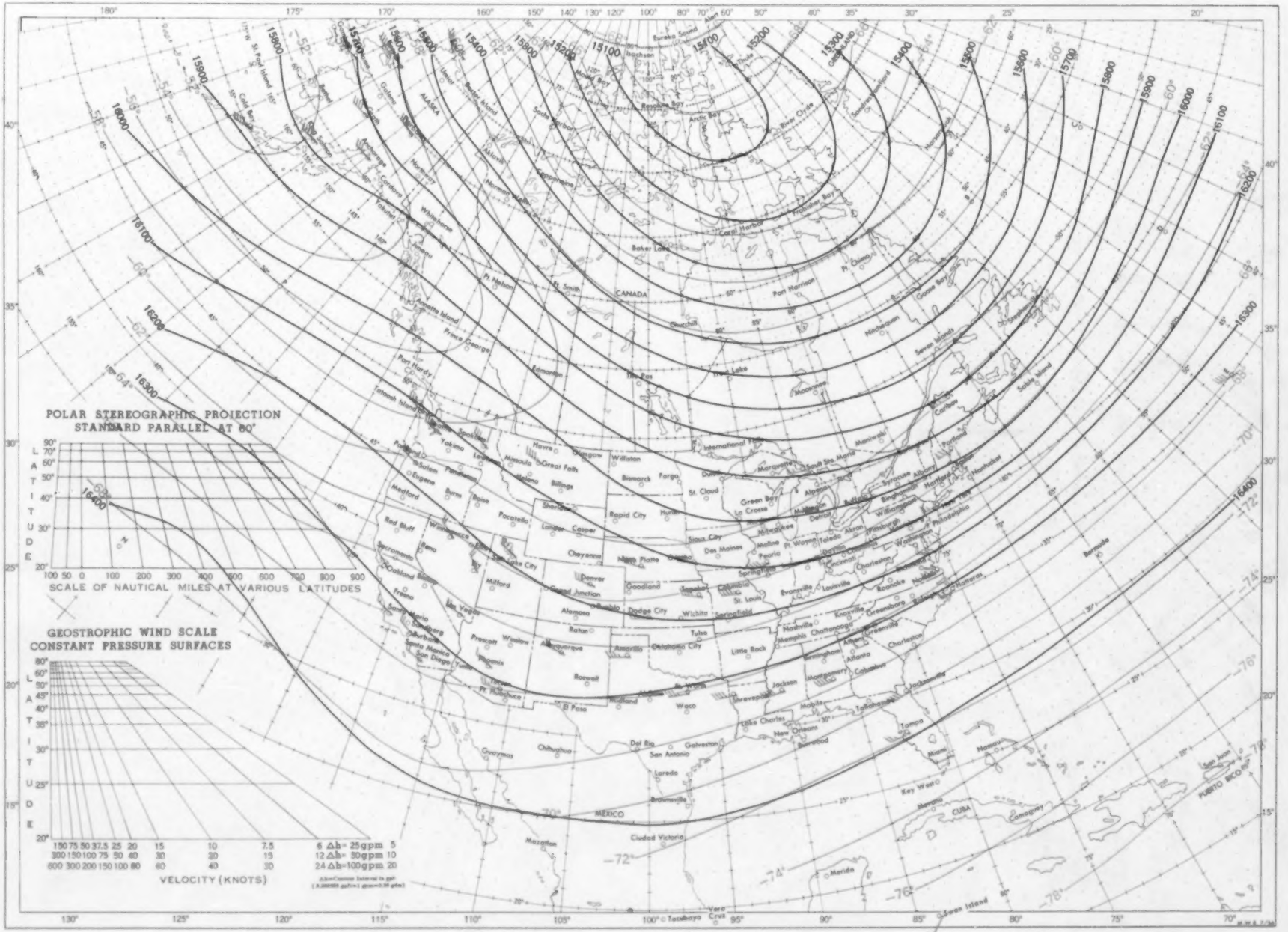
See Chart XII for explanation of map.

Chart XVI. 200-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

Chart XVII. 100-mb. Surface, 0300 GMT, December 1956. Average Height and Temperature, and Resultant Winds.



See Chart XII for explanation of map. All winds are from rawin reports.

PR

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First published in 1872, the Monthly Weather Review serves as a medium of publication for technical contributions in the field of meteorology, principally in the branches of synoptic and applied meteorology. In addition each issue contains an article descriptive of the atmospheric circulation during the month over the Northern Hemisphere with particular reference to the effect on weather in the United States. A second article deals with some noteworthy feature of the month's weather. Illustrated. Annual subscription: $4.00; additional for foreign mailing, $1.00; 40¢ per copy. Subscription to the *Review* does not include the *Supplements* which have been issued irregularly and are for sale separately.

WEEKLY WEATHER AND CROP BULLETIN

Issued on Tuesday of each week. A summary of the weather of the week and its effect on crops and farm activities over the entire country is presented, with short reports from individual States supplemented by maps of average temperature and total precipitation for the week and for the month. In the winter months a snow depth chart is included along with a table of ice conditions on rivers and lakes. Descriptions of, and data on, current unusual conditions, such as drought, floods, blizzards, etc., are offered, often with charts. Short articles on the application of weather data to agricultural and industrial pursuits are included. Annual subscription: $3.00; additional for foreign mailing, $1.00; 10¢ per copy. For period December through March, $1.00; additional for foreign mailing, 50¢.

CLIMATOLOGICAL DATA—NATIONAL SUMMARY

This monthly publication contains climatological data such as pressure, temperature, winds, rainfall, snowfall, severe storms, floods, etc., for the United States as a whole. A short article describing the weather of the month over the United States, tables of the observational data, and a description of flood conditions are supplemented by 17 charts. An annual issue summarizes weather conditions in the United States for the year. Annual subscription: $4.00; additional for foreign mailing, $1.50; 30¢ per monthly issue; 50¢ for annual issue alone. (More detailed local data are provided in the Climatological Data (by sections) for 45 sections representing each State or a group of States and Hawaii, Alaska, and the West Indies. Annual subscription, $2.50; additional for foreign mailing, $1.00; 20¢ per monthly issue.)

(Continued on inside back cover)

The Weather Bureau desires that the *Monthly Weather Review* serve as a medium of publication for original contributions within its field, but the publication of a contribution is not to be construed as official approval of the views expressed.

The issue for each month is published as promptly as monthly data can be assembled for preparation of the review of the weather of the month. In order to maintain the schedule with the Public Printer, no proofs will be sent to authors outside of Washington, D. C.

Use of funds for printing this publication approved by the Director of the Bureau of the Budget, February 9, 1955.

PUBLICATIONS OF THE U. S. WEATHER BUREAU

(Continued from inside front cover)

DAILY RIVER STAGES

Annual publication of daily river stages for about 625 stations on the principal rivers of the United States, with added data on elevation, drainage area, flood stage, and extreme stages for each station. Prices vary.

DAILY WEATHER MAP

Printed and distributed daily from Washington, D. C. This map consists of a 24'' x 19'' sheet on which is printed a large map of the United States showing the surface weather conditions as of 1:30 a. m., EST, and 2 small maps of North America, one showing the surface analysis at the 1:30 p. m., EST, the other the 500-mb. analysis at the 10:00 p. m., EST, previous to the large map. Precipitation areas and amounts and high and low temperatures for the 24 hours previous to the large map are also given. Occasionally short descriptive articles on some phase of applied meteorology or the Bureau's work are printed on the map back. Annual subscription: $7.20; 60¢ per month.

AVERAGE MONTHLY WEATHER RÉSUMÉ AND OUTLOOK

A semimonthly publication presenting for the coming 30 days by means of charts the expected patterns of average temperature and precipitation over the United States and the average atmospheric circulation patterns for the same 30-day period. Also given are corresponding charts for the past 30-day period showing the observed averages. A brief description of expected conditions is included. These charts are best suited for use where a general picture of future conditions over a wide area is needed. They should be used in conjunction with the short-term forecasts issued by the nearest Weather Bureau Office. Annual subscription: $4.80; $2.40 for 6 months (minimum subscription accepted).

RESEARCH PAPERS

The research paper series and the technical paper series described below are issued at irregular intervals as the material becomes available. Each Research Paper is a report of original research in which at least part of the answer to a specific meteorological problem has been worked out and is presented as a contribution to knowledge of the weather. Thirty-nine have so far been issued covering such subjects as precipitation forecasting for the TVA basin, the artificial production of precipitation, the application of the hydraulic analogy to atmospheric flow problems, etc. Prices vary.

TECHNICAL PAPERS

This series contains compilations of meteorological and climatological data on such topics as temperatures in the upper air, daily total solar and sky radiation, thunderstorm days in the United States, normal maps for the Northern Hemisphere, etc. Twenty-eight have been issued so far. Prices vary.

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